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PREFACE

This is the final number of Vol. 51 of the QUARTERLY TRANSACTIONS of the American Institute of Electrical Engineers and completes the Institute's published technical record for the year 1932. It embraces the Institute's 48th annual Summer Convention held at Cleveland, Ohio, June 20-24, 1932, and includes all technical committee reports, technical papers, and associated discussions formally presented at that convention.

In keeping with custom, a subject index and an author index covering all four quarterly issues for 1932 are published in this number; this year in an improved and extended form through which subjects may be located with greater facility.

As an explanation of inevitable inconsistencies that may be noted in this and the next subsequent numbers, it is significant to note that a change has been made in the basic reference dictionary by which the editorial staff is guided in the preparation of copy for publication. Beginning January 1, 1933, "Webster's International" dictionary (G. & C. Merriam) will be the editors' guide and arbiter for all published matter. Material composed for publication after January 1, will follow the new guide, but for economical reasons standing material will not be changed. Thus the two styles may appear side by side until all standing material has been published.

Engineering Subjects, Electrical and Cognate, in the Four-Year College Program of Electrical Engineering

BY ALFRED H. LOVELL*

Member, A.I.E.E.

IN the field of education for electrical engineering both the teacher and the practising engineer are vitally concerned; the teacher, because it is his life work, the practitioner because the young graduates are presumably trained to meet the specifications of his profession, to join its ranks, and to work beside him in the years to come. Obviously the working relations of man to man and the characteristics of the profession will be more or less determined by the nature of the training given to the young men who come into it at the rate of approximately 3,000 a year. In this sphere two great national organizations, the Society for the Promotion of Engineering Education and the American Institute of Electrical Engineers, have mutual interests and interlocking membership. It would seem well to set aside for the special consideration of the S.P.E.E., the methods of selection, the study of teaching methods, the operating details and organization of the curricula, etc., but certainly then, it is the special function of the A.I.E.E. to advise as to the economic and professional content and interrelations of the programs.

As a matter of background the study of engineering education by the S.P.E.E., 1923-1929, brought out a synthesis of opinion from teachers and engineers as to what engineering curricula should be, as follows:†

1. "Moderate diversity but tending away from specialization.
2. Dominance of the scientific and broadly technical content and emphasis.
3. Inclusion of a well-identified core of required subject matter.
4. Inclusion at all stages of subjects of purely cultural value.
5. Due emphasis (though not predominant) on the economic aspects of engineering and on its concern with administration and management.
6. Coherence of arrangement and coordination of related subjects.
7. Thoroughness rather than completeness of detail."

It will be remembered with regard to "specialization" that, instead of the general sense of the word as applied to the differentiation of instruction in accordance with the major divisions of engineering—civil, electrical, mechanical, etc., the S.P.E.E. used the term in the above discussion in a narrower sense as applied to a further degree of differentiation of curricula within the major fields themselves, such, for example, as the provision of distinct curricula in sanitary engineering, structural engineering and the like, within the major field of civil engineering. There was common agreement between the teachers and engineers that the primary purpose of instruction in specialized engineering subjects should be to teach fundamental principles and methods rather than to train for particular kinds of work. The engineers emphasized the opinion that specialization is out of place in undergraduate curricula and that thorough grounding in fundamentals is of paramount importance. Yet many of the teachers believed that in teaching specialized engineering subjects there is no essential conflict between preparation for particular fields of work and training in fundamental principles and methods, although the latter should always be the primary purpose. It has been a standard educational policy that principles are best taught in connection with their applications, and that the technical subjects proper should serve as media for teaching principles and the characteristic engineering methods of thought and analysis, instead of attempting preparation for specific types of practise.

The engineers were strongly in favor of extended training in economics and for a greater emphasis upon the economic phases in the engineering subjects proper. A large majority of the teachers, engineers, and graduates who were questioned indicated the belief that foreign languages, as taught at that time, were not of sufficient value to warrant their inclusion as requirements in the engineering curriculum. Both teachers and engineers were in agreement that shop work should not be required of all students, but only of those enrolled in curricula most closely related to the manufacturing industries. As a result of these definite criticisms and

SEMESTER HOURS AVERAGE REQUIREMENTS FOR GRADUATION IN ELECTRICAL ENGINEERING

S.P.E.E. Report, 1923-1929		S.P.E.E. Report, 1930	
Units	Subject Group	Subjects	Units
		Technological Subjects	
34.4	Electrical Engineering	Major Branch	39.0
42.1	Other Engineering	Other Technical Subjects	23.5
6.8	Engineering Electives	Electives	10.4
1.8	Non-Engineering Electives	Shop	1.6
0.1	Miscellaneous	Drawing	7.2
6.6	Phys. and Mil. Training	Phys. and Mil. Education	4.6
2.1	Foreign Language	Modern Foreign Language	1.2
4.4	Social Science	Economics	4.7
20.6	Physical Science	Physical Science	20.7
8.9	English	English	9.0
18.9	Mathematics	Mathematics	18.5
63.6	Total Non-Engineering		
83.3	Total Engineering		
137.6	Total Prescribed	Total Prescribed	133.0
9.3	Total Elective	Total Elective	10.4
146.9	Grand Total	Grand Total	143.4
55	Number of Institutions	Number of Institutions	51

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†Page 413, Report of the Investigation of Engineering Education, Vol. 1.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

recommendations, chiefly with regard to the preparatory and secondary courses in the curricula, many of the colleges have changed their requirements to meet the recommendations. The progress in this respect may be estimated by comparing the 1923-1929 table of graduation requirements for the first degree in electrical engineering with the corresponding table for 1930. Unfortunately, the two tabulations were not made in exactly the same subdivisions, but *Shop and Drawing*, listed as items in the 1930 report, are evidently included in the *Other Engineering* item of the 1923-1929 report, while *Engineering Electives, Non-Engineering Electives and Miscellaneous* of the 1923-1929 report are doubtless all combined into the item of *Electives* in the 1930 report. The other subjects, however, listed side by side appear to agree exactly.

The slight increase in English and economics with the corresponding decrease in modern foreign languages is notable. Still this does not show the full effect of the change since some colleges are still revising their curricula in this respect. For example the College of Engineering at the University of Michigan will change its requirements as of September, 1932, dropping 16 hours of foreign language or nontechnical electives in favor of 4 additional hours required in English, 6 hours required in economics, and 6 hours of free nontechnical electives.

It is believed then, that a great improvement has been made in the preparatory and secondary parts of the curriculum in electrical engineering as a result of the foregoing study and discussion. Some glaring omissions have been remedied and some old ideas have given way to new and present conditions. The fact that the recommendations after careful analysis by the colleges have been so widely adopted shows how valuable the recommendations of the practising engineers have been and how much they have achieved. We should expect, therefore, similar advantages to accrue from a study and discussion of the technical portion of our curriculum in something like the detail which was thus given to the preparatory and secondary subjects.

With regard to the technological portion of the curriculum in electrical engineering the tabulations of the total semester hours allotted to these subjects in the major branch of electrical engineering itself, those in other engineering fields, and those in engineering electives, in the 1923-1929 and the 1930 S.P.E.E. reports, are as follows:

SEMESTER HOURS REQUIRED FOR GRADUATION

1923-1929		1930				
Subjects	Units	Subjects	E.E.	M.E.	C.E.	Ch.E.
Elec. Engg.	34.4	Technological Major Branch	39.0	41.0	50.0	44.9
Other Engg.	42.1	Other Technical Subjects	23.5	22.9	18.4	21.6
Engg. Electives	6.8	Electives	10.4	9.3	8.4	6.7
Grand Total	146.9	Grand Total	143.4	145.5	144.0	146.4
No. of Institutions	55	No. of Institutions	51	44	51	41

It is noted that while there has been an increase in the central core of subjects in electrical engineering itself from 34.4 to 39.0, still the electrical curriculum contains less technical courses in its own field than any of the other major curricula, particularly those of chemical and civil engineering with their respective requirements of 44.9 and 50 semester hours in their own major branch. It would appear then, that the electrical engineering students take proportionately more of their technical work in associated departments and in electives, a situation which will heartily commend itself from the points of view of broad foundational training, and of freedom for the student to pursue his ambition in at least a slight degree into some particular field of his own choice.

The tendency to increase the number of semester hours of the technical requirements in electrical engineering was noted in the 1923-1929 S.P.E.E. report. That it prevailed and resulted in an 11 per cent increase is shown by the report for 1930. In view of the close approach to an upper limit should we not examine how scientific the training of a four-year electrical student should be? Doubtless we are all agreed that he must have, as an absolute minimum, say, some 16 semester hours of fundamentals in d-c. and a-c. machinery and steady-state circuits. But in the light of modern developments and in preparation for some known problems of the future how much further should we go?

The electrical engineers who were consulted in 1923-1929 as to which divisions of electrical engineering were of such importance as to warrant their inclusion in the training of all electrical students replied as follows:

Per cent favoring inclusion in all electrical engineering curricula	Subjects
67.5	Transmission and Distribution
59.0	Power Plant Engineering
57.0	Electric Machine Design
44.0	Industrial Power Engineering
38.8	Hydroelectric Engineering
33.5	Illumination
33.2	Electrochemical Engineering
28.4	Electric Railways
22.5	Telephony-Telegraphy
19.5	Radio Engineering

(It was taken for granted that a general foundation in the principles of electrical and magnetic units, laws, circuits and machines would of course be required in every case.)

In view of the developments of the past few years and of immediate future demands surely the subject of electronics and vacuum tubes should be added to the above list. Such a course should include an engineering approach to the theories of ionization, of the mechanisms of current flow and energy interchanges in ionized regions, and of thermionic, photoelectric, and other types of electron emission, as related to conducting gases at atmospheric and lower pressures. The study should cover thermionic vacuum tube characteristics and types of circuits and tubes suitable for rectifiers, amplifiers, detectors and oscillators. Not all of the

TABLE I—REQUIRED SEMESTER HOURS IN ELECTRICAL DIVISIONS
1931

Name of Institution	Fundamental Courses	Trans and Dist.	Power Plants	Elec. Mach. Design	Industrial Power	Illumination	Electro-chem.	Elec. Ry.	Tel. and Tel.	Radio	Electronics
Alabama Pol	24	5	8	4E	4E	2E			6E	6E	
Armour Inst	34	4.5	4.5		2						
Brooklyn Pol. Inst	18	3		2		2		2	5	2	
Univ. of Cal	18	5	4	3E					5	6E	
Carnegie Inst	33	2	5	9					2	3	
Case School	27	5	1		3E	6		1	3		3E
Cornell Univ	33	3E	3	4E	2E	2E		2E	4E	3	
Georgia Tech	24	3	5E	2		3E		5E	2	3E	3
Harvard Univ	16	7		3E					3E	3E	3
Univ. of Ill	22	3E	4	2		1E				6E	
Univ. of Iowa	22	6E	5E	3		3E			6E	3E	
Iowa State	24	2	2	2E				2E	2	2E	
Johns Hopkins	30	2.5	2.5	4		2.5		2.5		5	
Univ. of Kansas	15.5	4	3		3E	2.5		2E	5E		
Kansas State Ag	26	3E		3		3E			3	3E	1E
Lehigh Univ	25	6E	3	6E	2E			3E	3E	3E	
Univ. of Maine	27	3	3	3		3		3	4.5	4.5	
Mass. Inst. Tech	19	5	6E	6E	3E	3E		6E	3E	3E	
Univ. of Mich	16	4	5	4	2E	2		2E	4E	6E	4
Univ. of Minn	27	4E	6E	4	2E	4E		2E	6E	6E	2E
Univ. of Nebraska	22	4E	4E			2E		3E	4E	3E	
Ohio State Univ	20	2E	2E	4E		4E		3E	6E	3E	2
Penn. State College	20	5E	2E	2E	2E	2		3E	3E	2E	
Univ. of Pittsburgh	17.5	3	2	2	4	3		2	1.5	1.5	
Princeton Univ	16	2	3E	6	2E		4E	2E			
Purdue Univ	26	6E	6E	5	3E	3E		3E	6E	6E	6E
Renss. Pol. Inst	21	4	3	4	2	2	3	2	1.5	1.5	3
Texas A. & M	32	3	3	6E	3E	3E			3E	3E	
Union College	28			3							
Virginia Pol. Inst	18	6E	6	3						6E	
Washington State	23	5	2E	2		3E		3	3		3E
Univ. of Wisconsin	24	6E	3E	3E		3E			3E	6E	3E
Yale Univ	32	3E	3E		3E				3E	3E	3E

E = elective.

subjects in the above tabulation are standard requirements in the college curricula but nearly all are represented in the programs as requirements or available electives, the exception being perhaps electrochemical engineering which in practically every case is offered in the departments of chemistry. The following study shows what a number of representative schools provide in required and elective courses in the above subjects:

It is notable that there is a great consistency for the first four columns of Table I in that nearly all colleges require a group of fundamental courses of not less than 16 hours and also provide one or two courses in transmission and distribution, power plants, and electrical machine design. The few schools whose catalogs do not show a course in electrical power plants provide a strong preparation in the courses they schedule in the heat power division of mechanical engineering. There is also strong agreement in using the field of power plant engineering as the vehicle for applying economics to engineering problems. In the remaining columns of the table the courses offered are mainly elective, the restriction of time allowing the undergraduate student probably not more than one, or at most two, courses in any division. Many colleges offer several sequential electives in the various divisions but the courses are principally for graduate students. There are difficulties in analyzing the curricula in these divisions. Illumination may in some cases be offered in the department of physics; telephony, telegraphy, radio, and electronics may be combined in various ways in courses given as communication engineering.

In order that the preparation shall have a proper breadth and that the graduate shall understand something of the problems facing his colleagues, what should be the training of electrical students in the fields of the associated technical departments of mechanical, chemical, and civil engineering?

In mechanical engineering the electrical student has need of a fundamental course dealing in elementary thermodynamics, steam, fuels, boilers, steam engines and turbines, condensers, internal combustion engines, and the general problem of a power plant. Some time in steam laboratory would be valuable to vitalize the work. It will be necessary to establish the standard ratings, efficiencies, methods of governing, and speed regulation of the prime movers here so that they may be transferred to the electrical courses concerned with the generator.

To chemical engineering we look for a knowledge of the engineering materials with which to work. For general structural and power work every student needs an elementary knowledge of the manufacture and properties of the ferrous and non-ferrous alloys, cements, clay products, protective coatings, fuels, boiler scale, and water softening together with associated laboratory experience in mechanical working and heat treatment of the various metals, welding practise, protection against corrosion, etc. In addition to these widely used materials which are generally covered in the

TABLE II—REQUIRED SEMESTER HOURS IN COGNATE ENGINEERING DIVISIONS
For Students of Electrical Engineering
1931

	Mechanical			Civil				Chemical
Name of Institution	Heat Power	Machine Design	Shop	Structural Design	Hydraulics	Surveying	Ry.	Engineering Materials
Alabama Pol	10		4		3	3		2
Armour Inst	9	4	6		4	1.5		1
Brooklyn Pol. Inst	9	1	2	2	3			1
Univ. of Cal	9	2	4		6	6		
Carnegie Inst			7		3	2		4
Case School	7	3	2		3	3		1
Cornell Univ	11	4	4		2	3		6
Georgia Tech	8		3		4	2		2
Harvard Univ	8	4	1		3			4
Univ. of Ill	11		6		3			
Univ. of Iowa	5		3		2	3		
Iowa State	8		4		3	2		2
Johns Hopkins	13				3	3		3
Univ. of Kansas	6.5	3	4		3	3		1
Kansas State Ag	9	3	5		4	2		2
Lehigh Univ	8				3	4		3
Univ. of Maine	7.5		3					
Mass. Inst. Tech	8		3		3	2		
Univ. of Mich	4	3	2	3	3	2		3
Univ. of Minn	6		5		3			
Univ. of Nebraska	7	6E	6E		3E	6E		
Ohio State Univ	6	6	6		2			
Penn. State College	10	4	4		2	1		2
Univ. of Pittsburgh	5	4	1		2	2		
Princeton Univ	10	3			3	2		2
Purdue Univ	7		4		4E	2E		
Renss. Pol. Inst	9	2	8	3	4	2	3	1
Texas A. & M	8		2		3E	2		
Union College	6				3	6		
Virginia Pol. Inst	6		6		3	2		
Washington State	9	2	4		3	3		4
Univ. of Wisconsin	9	3	4		3	3E		2
Yale Univ	6					3		2

E = elective.

common introductory course in chemical engineering, the electrical student has a special interest in the silicon steels, in oils and papers, in cold and hot flow materials, in phenol plastics, varnishes, tapes, and mica. Seemingly no course given at the present time covers these materials which are so essential to the electrical designer. They should be included in the more comprehensive list of fundamental materials for an electrical student.

In civil engineering a common basic structural design course may follow some eight semester hours of engineering mechanics or the same field may be covered as applied mechanics in the last named department. At Michigan the preparatory design courses in mechanics cover statics—3 hours, strength and elasticity of materials, 4 hours, laboratory in strength of materials, 1 hour, and dynamics, 3 hours. In a fundamental structural design course we feel that the student should have some elementary training in analysis of stresses, moments and shear, for wood, steel and concrete beams, roof trusses and columns; beams and slabs in reinforced concrete masonry; an introduction to soil bearing theory, bearing power of piling and settlement; together with some contact with electric welding of frames and machine structures.

The above tabulation of the curricula in electrical engineering for the schools listed, shows the semester hours required in cognate engineering subjects:

While there is almost a general agreement as to the necessity for courses in heat power, shop work, and hydraulics there is evidently a considerable difference of opinion as to the need for training in surveying and in the mechanical features of machine design. Again almost half of the programs offer no training in engineering materials and only three curricula call for a structural design course after a preparation in engineering mechanics.

In view of these differences of opinion among teachers not only as to the subjects to be included in the fundamental training of the student but as to the time spent upon them as well, I feel that consideration and study and the gathering of suggestions from the practising members of our profession would be very much worth while.

Discussion

S. M. Dean: Because it is necessary that an engineer, like anyone else, shall thoroughly enjoy his job if he is to be successful and because an increasingly large proportion of engineers are before many years finding themselves in administrative positions, I wish to discuss Professor Lovell's paper from a somewhat non-technical point of view.

I agree that any electrical engineer must have a basic training in the fundamental concepts upon which electrical development and nomenclature are reared. Referring to Professor Lovell's Table I, I should include in this first and prescribed group the fundamental courses as well as transmission and distribution and also, as he has suggested, electronics. Having progressed that far I should offer as electives a rather wide range of the more specialized subjects by way of determining the "natural bent"

of the student as well as showing him into what the various branches of the electrical engineering profession lead. A student's selection of these courses would, of course, be carefully guided.

Two very important characteristics of the successful administrative engineer are his ability to take a broad view of any situation and his ability to set forth his ideas in a logical and convincing manner.

It seems to me as I look back at my college training that I could have been greatly aided by having a better idea of the course of events by which electrical engineering came up and where it stood when I entered the field. It would, of course, have been the story of the surmounted obstacles and of the men who contributed to the successful development of the various steps, both from the strictly engineering side as well as the commercial. I feel very strongly that a carefully planned course of this kind should be included early in the student's technical course. Such a course would call for the abilities of a master teacher and its importance would justify it.

Contributing also to this breadth of view are the broad range of cognate subjects suggested by Professor Lovell. I believe I would go so far as to include the more important of them to the possible exclusion of some of the more highly specialized courses in the electrical list of electives, because it is less difficult later to acquire an understanding of matters within one's professional field than those outside.

Laurance E. Frost: Professor Lovell concluded his paper with a call for suggestions from practising members of the engineering profession. Of course, no one could take greater pleasure in responding to such an invitation than one who has had the privilege of being a student in Professor Lovell's own classroom as I have.

Professor Lovell refers to a list of ten major divisions of electrical engineering which have widely been considered as worthy of inclusion in the training of all electrical students. He also points out another one, electronics, which has come to the fore so much in the last few years that it can hardly be denied admission to the list. So the list has grown to eleven items. And who can doubt that future years will bring other new fields into this list faster than old ones are dropped from it? Reflecting for a moment that it takes the best part of a lifetime for a man to attain a mastery of the technical phases of one or two of these fields, we may well pity any student who hopes to know them all in four or five years.

It is gratifying to a practising engineer to find it apparent from Professor Lovell's paper and others that, in the technical realm, many engineering educators are still concentrating on the basic and indispensable concepts of physics, mathematics, and chemistry, which form the background of all engineering, rather than diluting the training over-much with studies of current engineering practises and applications. A college course hasn't room for much more technical material than these fundamentals if they be treated with the thoroughness they deserve. It seems to be agreed generally that industry is in a better position than the colleges to teach about current engineering applications.

In the eleven short years since my own graduation it has been my good fortune to come in contact with many young men soon after their entry from college into the practising profession. From careful observation of their work it has been clear that those who had acquired a thorough knowledge of basic engineering principles have been the ones best adaptable and best able to meet their engineering opportunities, in spite of initial unfamiliarity with the details of particular applications.

May I then add my voice to the plea that in the teaching of electronics, or any other new field, most of the teaching effort be directed toward the basic principles which will be pertinent to future development and usage rather than toward description of present day practises which are susceptible to rapid change.

R. E. Hellmund: The study and statistics presented in Professor Lovell's paper are very instructive, especially since they indicate a number of points in which improvements in the curricula seem to be very necessary. It is most surprising and regrettable that almost one-half of the schools listed in Table II do not give any training in the mechanical features of machine design, and also that a very large percentage do not offer any courses in engineering materials. It cannot be stressed too strongly that all component parts of electrical machines and apparatus present mechanical problems and that the greater part of the work of electrical design engineers has to do with the mechanical phase. Hence there can be no doubt that curricula for designers should include training in the mechanical features of design and engineering materials. Although work on heat power and hydraulics, courses which are so generally represented in the tabulation, is of course of importance to future central station engineers, it would seem well worth while to give some of the time now devoted to these subjects to mechanical design and engineering materials; at least it would seem that good courses on these subjects should be optionally available to those students wishing to go into design work. It is also believed that these courses should be taken by designers in preference to any work on surveying.

Professor Lovell's suggestion that this entire subject be given consideration and study is very timely.

D. C. Jackson, Jr.: Since some data for Professor Lovell's paper were gathered from the college catalogues for 1930-31, changes of curricula which were in process at that time are not included in his tables. Both the University of Kansas and Kansas State College made during the past academic year a number of changes in their electrical engineering curricula. In order that Professor Lovell's paper may be up to date as far as these two institutions are concerned, Tables I and II should read as follows:

TABLE I

	Fund. Courses	Trans. & Dist.	Power Plants	Elec. Mach. Des.	Indus. Power	Illumination	Tel. & Tel.	Radio	Electronics
Univ. of Kansas	18	4	3*		3E	2.5	3E†		
Kansas State	26	3E		1		3E	3	3E	3

*Required in power and machinery option, elective in communication option.
†Elective in power and machinery option, required in communication option.

TABLE II

		Heat Power	Mach. Design	Shop	Hydraulics	Surveying	Engineering Materials
Univ. of Kansas	Power and Machinery	6.5	3	3	3	3	1
	Communication	5	3E	3	3E	3	1E
Kansas State		9	3	4	3	2	2

The data with regard to Kansas State College were obtained from Professor R. G. Kloeffler, head of the department of electrical engineering at that institution, since I knew that certain changes had been made rather recently in his department.

The changes in the electrical engineering curricula of the Kansas State College of Agriculture and Applied Science, and of the University of Kansas, tend to substantiate the trend indicated by Professor Lovell. Kansas State is requiring electronics instead of making it elective and the hours allocated to this subject are now greater in number. Kansas University has a larger number of hours given over to fundamental courses in electrical engineering and now has rather more than sixteen, which Professor Lovell points out is the minimum for fundamental electrical engineering subjects in those institutions which he used in his study.

Lyman F. Morehouse: In Table I of the paper which shows for various schools the division of required semester hours in electrical engineering, and taking the University of Michigan as an example, it is noted that the required "fundamental" electrical courses total 16 hours; also, that the required courses in transmission and distribution, power plants, electrical machine design and illumination, total 17 hours. The 16 hours of fundamental courses are, obviously, fundamental courses in dynamo electric machinery, and would appear to me to be specialized courses in the power field rather than broad fundamental courses. Special courses outside of the power field are all elective. The same seems to be generally true of other institutions.

It may be questioned whether all of the required work should not be given in truly fundamental courses, in which the broad fundamentals would be illustrated from every phase of electrical engineering, or, if this is impractical, that the required courses other than those designated as fundamental cannot have a more general content and be more widely illustrative of modern electrical engineering in its broadest application. For example, transmission and distribution might well cover the entire range of frequencies utilized in modern electrical engineering, and include not only power distribution but telegraphy, signaling, telephony, radio, and perhaps television.

It is stated that the course in "electrical power plants" is usually employed as a vehicle for applied economics. It seems obvious that economic principles could be applied with just as great benefit to other types of installations as to steam power plants. The suggestion might be added, therefore, that in studying the contents of the electrical engineering part of the curriculum, attention might well be given to broadening it and balancing it in line with what appears to be the present trend of the electrical field—that is, the trend toward new things involving all parts of the electrical frequency range, rather than concentration on the production and distribution of 60-cycle current. It seems to me that this is what an education in electrical engineering of the future requires.

L. W. W. Morrow: A study of the technical content of engineering courses is very desirable and Professor Lovell presents data to sustain this suggestion. In my opinion this study offers the greatest opportunities for improvement in technical education and is most needed at this time. All aspects of engineering change rapidly both in theory and practise and it is essential that the technical contents of engineering courses keep abreast of the art. The scope and depth of fundamental science should be increased and changed each year and the applications of principles should be made to the current engineering problems encountered in practise. Yet I have heard it asserted that the colleges are at least five years behind the times in their technical course content as regards both modern theory and modern practise.

It is interesting to study Table I of the paper which shows the required semester hours in the electrical divisions of 41 leading colleges.

The data in this table raise several questions at first glance:

1. What reason is there for the hours devoted to fundamental courses to vary from a minimum of 15.5 to 34?
2. Why is there no correlation between fundamental course hours and the additional hours of either required work or electives?
3. Why are so many electives given in specialized branches of electrical engineering?
4. Why, for example, do courses in electric railways persist in a large number of colleges while comparatively few give courses in electrochemistry and electronics—live and active field engineering divisions?
5. Why does electric machine design persist so greatly especially since this is applied to machines that have been standardized for many years?
6. How can any student be broadly trained in electrical engineering if he is forced to specialize in limited branches just as soon as he finishes his fundamental courses?
7. Why is it necessary or even feasible to teach specialized courses such as power plants, illumination, transmission and communication in undergraduate courses?

A general reaction to this table as a statistical summary of technical courses is that it shows very vividly an antiquated, superficial and cumbersome content for the technical engineering courses. In my opinion, based upon my experience as a teacher and as an engineer who studies all field problems as an editorial observer there is a very great opportunity to improve the technical content of engineering courses. This should be based entirely upon the principle of teaching the latest and best theoretical principles by applying them to current engineering problems and practises. There should be no attempt to specialize and the technical content should consist of a basic fundamental course to be given all students in their junior and senior years with a few electives based upon choice of specialized theory rather than commercial divisions of engineering as found in the field.

Let us glance briefly at the field and see what problems confront practising engineers and then perhaps we can grasp the point of view I have expressed.

Power Plants. Hydro stations and all equipment are very greatly standardized with little opportunity for improved efficiency except in the design of governors, water passages and waterwheel controls. Steam stations at normal pressures are standardized except for control of temperature over wide load ranges. In the high pressure—high temperature range there is a problem of materials to be solved. The two-fluid heat cycles are in process of development. Vibration of turbine parts and shafts, clearances, effects of corrosion and erosion of blades—these are current technical difficulties. A detailed study of a Corliss valve or of a simple steam engine as taught in college helps not at all on these problems. Fundamental thermo- and hydro-dynamics and a knowledge of mechanics and materials are the tools an engineer needs.

Transmission and Distribution. We are now dealing with network circuits. Our problems are in control, relaying, metering and fault elimination. The circuit equations are complex because of the network and only new mathematical tools such as symmetrical components and hyperbolic functions can be used to get results. We have distorted electric and magnetic fields, multiple path electric circuits and a mass of equipment that makes impossible an approach by use of a simple circuit equation or even the Fourier series so well drilled into undergraduates. Beyond these current field problems transmission is in a development stage through the application of electronics and ionization principles to new types of apparatus. Even our transmission structural design problem is one of vibration and fatigue wherein the book formulas give little aid.

Industrial. Very little change in design or performance has been had in years with standard motors and generators. Their application is largely that of control and their design is largely that of working materials at maximum thermal limits so as to

reduce costs. Possibly the two live problems today are control and electric heat. Electromagnetic controls of all types are confronted by the new vacuum tubes and photoelectric cells that may replace them. Electric heat problems are mechanical and metallurgical rather than electrical.

Electrochemical processes in industry are on the increase, chromium-plating, electro-deposition of white lead, the making of synthetic resins, electro-winning of ores—no field is so active in development or more promising. How many undergraduates know the first principles of electrochemistry?

In the realm of electronics a vast field is opening up. An executive of a large manufacturing company said to me the other day "I would like $10,000,000 and a group of our best scientists to specialize in electronics for a year or two. I believe the biggest future in industry lies in this field." Vacuum tubes, photo-cells, ionization phenomena, thermionics—all the new tools and new theories are ripe for use and students should know the principles and have sufficient experimental work to use them. Yet the course still is filled with motor design and standardized rotating machine tests about which no major problems are associated and in connection with which the market has an over supply of engineers.

One could touch illumination with gaseous conduction and ionization as basic elements instead of resistance filaments. Radio with its untouched possibilities for power transmission and for directive and selective energy control is another live topic. Even the new idea of air conditioning introduces new fundamentals for students.

I point out a few of these field conditions in order to repeat my points about the technical content of college courses.

1. Stick to theoretical principles and apply them to all current engineering applications.

2. Eliminate the old, the standardized and the obsolete principles and applications and replace them with the new and live theories and applications.

3. Do not specialize in terms of arbitrary and artificial field divisions of engineering, but require all students to take the same fundamental course with a few electives in specialized theory instead of practise.

A. E. Silver: The college education of engineers is a matter of mutual concern to the educator and practising engineer. Constructive suggestions of greater value for the keeping of principles and curricula apace with advances in the art, should be forthcoming from the latter group if they would give closer attention to these important problems and if their cooperation is enlisted. Few of us adequately reflect and weigh how our education has been extended and modified since leaving college or how the prescribed courses of study, or our selection of them, might have been improved for the purposes of meeting the constantly advancing requirements of experience.

The work of the Society for the Promotion of Engineering Education is commendable and the conclusions seem well founded. Possibly, however, because of the time lag in the evolving and applying of such principles, greater weight should be given to looking reasonably into the future. This should be beneficial if it is found that programs can be brought more nearly abreast of conditions as encountered by the graduates.

For the education of an electrical engineer, it is a real question whether the student should be required to take all of those subjects that are considered fundamental and basic for his broad technical, economic and cultural education, or whether a considerable degree of latitude should be allowed for specialization or the pursuing of courses to the particular liking of the individual student. If the student could be guided early to discover for himself his caliber as engineering material, it should be of great assistance to the individual as well as the educator in determining this question.

For the broadly promising engineering timber, there might be required basic courses in physics, mathematics and electrical engineering and, with proper guidance, a large portion of the balance of the college work selected from a well formulated group of fundamental courses. These would include practical use of the English language, economics, business, introductions to all the important branches of electrical engineering and familiarity with the allied engineering fields. Non-essential subjects could be made of secondary importance, *e.g.*, modern languages, assuming these reasonably covered in preparatory school, would be subjects for later specialization.

In my opinion, natural ability justifying a four year course should be devoted primarily to the laying of a foundation, learning the principles of accomplishment by the effective directing of the forces at hand, acquiring the trait of making one's knowledge available and of value to others and finding one's natural self, leaving specialization largely to graduate work and to one's later initiative and experience.

A. E. Knowlton: There should be generous support of Professor Lovell's plea that the electrotechnical content of the curricula should be surveyed. But much of the value of such a survey would be lost by placing too much emphasis on the statistical data about semester hours and division between prescribed and elective subjects or inferring too much from the catalogue descriptions of the courses. Every one who has ever been in the teaching profession knows that catalogue descriptions of courses are seldom a true index of their character or objectives. The students in them however devise labels that are often far more indicative although not always expressed in language that the faculty could employ. Catalogue statements and credit hours mean little.

We hear much about reversion to fundamentals and elimination of the curse of specialization. But there seems to be no agreement on what constitutes the fundamentals. Are the fundamentals to be merely the basic technologic facts upon which the early branches of the electrical arts were founded? If that is true then it accounts for the adoption and retention of a curriculum built on the concept of an industry that had two or three well-defined branches. Such a practise might have been appropriate while the branches of the electrical art were few and well-defined. But as sub-divisioning and specialization proceeded within the electrical engineering field, education followed suit after the normal time lag. The resulting specialization has caused some concern and much criticism.

One way out would appear to be to review the content of fundamentals. Apply to every item the test of its broad applicability over the whole gamut of energy magnitudes and diversified applications. Those phenomena and principles which have greatest adaptability to the widest range of electrical activities would appear most entitled to the rank of fundamentals. On this basis an extended discussion of commutation or of the circle diagram of the induction motor might be found unjustifiable. In fact much of machine design would suffer in the face of that kind of analysis.

The other phase of correction suggested by one who has had an opportunity both to teach fundamental and specialization courses and to observe at close range what practising engineers deem to be the pressing matters of the moment, is that more stress be placed on the functional significance of the electrical phenomena and the physical equipment devised to exploit them. No effort on the part of the teaching profession can keep the curriculum abreast, let alone ahead, of the kaleidoscopic changes in the field of practise as long as the courses follow a vertical cleavage in imitation of the industry divisions. But if the functional tasks are allowed to determine the course content the horizontal character of the set-up will give the subject matter an incidence upon every branch of the art which involves the exercise of those functions.

To make the point specific, there is the function of generation. This does not mean dynamos and turbo-generators alone; it

means batteries, photo-electricity, transmitters, piezo-electricity. There is the function of magnetization. The function of conveyance of energy embraces transmission, distribution, radiation and waves. There is the function of insulation as contrasted with conduction. There is the function of control and the function of protection against extraneous influences. Most of these appear in some form in every significant branch of the industry. A student drilled in these fundamental functional concepts would acquire a confidence or aptitude and adaptability now lacking in many graduates. He would see the unity of electrical technology where he now too often sees only a narrow cellular structure.

Incidentally, if a further opinion is permissible, some one of these functional subjects could well be carried to just as thorough an exhaustiveness as time permits. It makes little difference whether it be metering, amplification or protection or something else as long as it goes as far as current literature and current thinking have gone in that one specialty field. The method by which engineering industry improves its practises and its economics is the crucial thing to incorporate and this can be done by the through-to-the-end analysis of some appropriate field. Take the function of protection for example. It involves lightning, grounding, fusing, relaying, insulation coordination, circuit breakers, shielding, flux control, reactances, stability, unsymmetrical vectors, arresters, traveling waves, inductive coordination, electrolysis. Anyone would have difficulty in suggesting a better way to add zest and comprehensiveness to electrical education than to place it on such a functional basis, especially if the project idea is employed to carry analysis to finality.

Reverting then to the topic of the paper, the plea is made that the curricula be studied as suggested by Professor Lovell. That little stress be placed on statistical data. That the bulk of the effort be devoted to disclosing the objective and the motivating purpose of each subject and the course as a whole. That the prescribed courses be so surveyed and recorded as to indicate clearly whether the so-called fundamental content would fall under a horizontal or vertical category. That a measure be established in advance to determine what are the common denominator fundamentals of electrical power, transportation and communication. That the content of each course be tested to determine the extent to which it includes these fundamentals and excludes other material. Such a procedure might succeed in silencing the accusation from alumni and industrial employers that colleges "specialize too much and do not stress the fundamentals."

W. W. Lewis: Engineering graduates are absorbed through three main channels: the large manufacturing companies, the large public utilities and miscellaneous small manufacturing companies, public utilities and industrial plants. The first two groups maintain more or less extensive training courses to equip the graduate for the requirements of the particular company, and this training may be broad or special, depending on the extent and activities of the company. The main requirement of the graduate for these groups is a broad training in the fundamentals, such as physics, mathematics, chemistry and a-c. and d-c. machinery. The third group requires the same broad training plus a specialized training, which will fit the graduate for immediate usefulness in the company or industry by which he is employed.

Since very few know until very shortly before graduation in which group they will be placed, obviously it is necessary to give all students the broad fundamental courses plus a number of specialized courses. The specialized courses have the advantage that principles are more readily understood and become more interesting when connected with a specific application. Interest in a special course may guide the student to seek employment in a particular industry. Specific knowledge applicable to an industry will help the student to swing into his work, even though the course may have been brief and the knowledge gained meager.

It follows that on account of the indefiniteness of the ultimate industrial destination of the student, the college is obliged to teach a diversity of subjects. It would be impossible to arrive at more than a general agreement as to the relative importance of the various subjects, as those in different industries are bound to have different points of view and the colleges themselves are subjected to local considerations.

We agree that the subject of electronics is becoming increasingly important and should be given a place in all electrical courses. Personally, we would favor the elimination from the electrical course of surveying as unnecessary. Foreign languages could also be eliminated, as the courses are usually too inadequate to be useful. Otherwise, practically all of the courses listed in Tables I and II are desirable.

Philip S. Biegler: At the conclusion of Professor Lovell's paper he makes the statement that suggestions from practising members of the profession would be very helpful in the formulation of electrical engineering curricula. With this same idea in mind the College of Engineering of the University of Southern California organized an Advisory Committee made up of prominent engineer-executives of this vicinity somewhat over a year ago. This committee has made a study of engineering curricula of the College of Engineering during the past year, meeting for two hours about every two weeks. We feel that the Advisory Committee has and is contributing a very valuable service in making a critical study of curricula and methods of instruction at this university. In general, these men agree that specialization in engineering instruction should be minimized and that our six curricula in engineering should be made as much alike as practicable. This is, of course, in line with present trends in engineering education. They believe that the training in English for engineering students is still inadequate. As one of the members put it: "Not all engineers use calculus in engineering practise, but they all do use English."

The Committee recommends the increase in training in economics and economic aspects of engineering. It doubts the justification of such a course (which might be called a specialized course) as power plant design. It recommends that rather than courses in structural design on reinforced concrete, other students than civil engineers take a single course in design dealing with wood, steel, and concrete. Our electrical engineering department has developed a four unit course in electronics or "high frequency" with the idea that this is a fundamental course and not specialized.

Alfred H. Lovell: The 16 hours of "fundamentals" quoted by Mr. Morehouse include:

Principles of electricity and magnetism............4 hours
Direct current apparatus and circuits.............4 hours
Alternating current apparatus and circuits........8 hours

so that perhaps only 6 hours is confined to dynamo electric machinery while 10 hours is general. Even our transmission course (electromechanics-4 hours) is based on the general equation of the circuit with the examples taken from both the power and communication fields. Thus Mr. Knowlton's pithy comments on the names of courses are amply confirmed.

Obviously economic principles could be applied to other types of installations than to power plants but where will the teacher find in the current technical literature a body of data covering installation and performance costs, maintenance, depreciation, rates, etc., comparable to that given for the power field?

I believe that Mr. Morrow's criticism is very just,—our technical layout is antiquated. However the situation is not as bad as it appears. Here again names of courses are misleading. I think the majority of our so-called machine design courses really cover studies in heat storage, transfer and dissipation, field mapping and calculation, etc. We still offer electric railways because our Transportation Department requests it. Still I do not see how we can teach "the latest and best theoretical principles" without some proper ground work. How will a

student appreciate that any theory is latest and best without a contact with the orderly development in that field and an appreciation of the economic factors that forced improvement and new design? Since the latest theory is very likely to be closely related to laboratory research there is also a serious limitation of laboratory equipment. Perhaps not half of our laboratories possess a cathode ray oscillograph. We now can bring the student interested in transmission through a well rounded foundation plan to a knowledge of the main elements of control, relaying and fault elimination, with ability to use hyperbolic functions and symmetrical components in a simple network. I feel that is all that can be expected of a four-year program.

Mr. Knowlton's suggestion of a horizontal division of electrical phenomena and related equipment is most interesting and startling. After a fundamental preparation such a plan would offer wonderful opportunities for development and coordination through the entire field of electrical engineering. Our course in electronics seems to be developing exactly along this line. It would appear to call for a complete reorganization of present teaching plans into a research plan such as where a new development is carried into all available fields. It would also call for fundamental changes in teaching staff assignments since present teachers have been selected largely on account of experience in some vertical cleavage of an industrial division.

I am sure that teaching staffs will give careful consideration to the recommendation that fundamental courses should be reexamined and retested for broad application. Also much will be gained through study of the other carefully considered criticisms and suggestions which have been given in such a fine spirit of cooperation.

Educational Aspects of Engineering and Management

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INTRODUCTION

SHALL a common educational program be employed as a preparation for engineering and for management, and if so shall it be planned primarily for engineers, as in the past, or for managers; or shall there be independent programs for each group? In view of clear trends of experience—of the movement of engineers into management—shall we conclude that technical engineering has proved to be an effective and sufficient training at college for those who may later enter the field of management? Or, shall we consider it necessary radically to modify all engineering curricula in order to prepare men *primarily* for management? Or, again, and from the same experience, shall we plan separately for each? And, having answered this, what should the plan be?

The general subject of engineering education has had searching and extensive study during the past fifteen years. The first broad study was by Dr. C. R. Mann for the Carnegie Foundation[1] in 1918; the second, by the National Industrial Conference Board[2] in 1923; then followed the comprehensive investigation and study by Dr. W. E. Wickenden for the Society for the Promotion of Engineering Education,[3] which was reported, together with the recommendations of the Board of the Society, in the period 1926-29. The S.P.E.E. study covered practically all phases of the subject including not only a study of the purely educational aspects, but also an analysis of function, salary, and opinion of practising engineers. Other studies relating to individual aspects—such as functional distribution, salary, etc.,—were also reported in this period by various organizations; Eta Kappa Nu,[4] American Telephone and Telegraph,[5] American Institute of Chemical Engineers,[6] Purdue University,[7] Yale University,[8] and the American Society of Mechanical Engineers.[9] The latter is a recent, very comprehensive statistical study dealing with functional distribution and salary of mechanical engineers. And finally, there has been extensive discussion of it all in the literature. Thus, there now exists a prodigious mass of material in all stages from raw data to carefully thought out conclusions and recommendations. As one attempts, by casual study, to form a rational opinion regarding educational policy, as this relates to engineering and management, one is likely to become lost. At least this was the writer's experience. Even the carefully framed conclusions and recommendations of the S.P.E.E. seem inadequate in certain respects, in view of later facts—for instance, those brought out by the A.S.M.E. survey; also one wonders whether all of the data collected by these various agencies are consistent, and, finally, whether the basic thoughts underlying proposed educational policy are all well taken. A careful study was therefore undertaken of the new facts, their historical setting, and of the basic views underlying prevalent thought. From the perspective thus arrived at, a future educational policy, which seems appropriate to the writer, was framed. Since there are doubtless many others interested in this problem who have experienced a similar confusion in the face of conflicting opinion and the great tonnage of undigested data, it seemed in order to present this study.

The proposed policy turns out to be in most respects consistent with the recommendations in the Mann Report and the S.P.E.E. Report, and also with those particular proposals of the National Industrial Conference Board Report which deal with the educational program for engineers. There are some respects, however, in which important differences do arise. These are largely questions of emphasis, some of which are raised as a result of the new facts. Yet there is one phase of the general problem which does not seem to have been considered seriously in previous studies, and that is the practicability of an effective training for general management in non-technical industry, by other subject matter than technical engineering. This possibility is recognized in the present study.

FACTS

The first step in the study was to ferret out and compare the major, relevant facts from the various surveys. The summary facts thus indicated, which apply certainly to mechanical, very probably to electrical, and possibly to most other engineering graduates, are as follows:

1. About one-half of all such engineering graduates by the time they have reached 40 years of age, have gone into industrial work primarily executive in character. These include two approximately equal groups.
   a. Those whose duties have *required* a substantial *technical engineering knowledge.*
   b. Those whose duties have not required such knowledge.
2. Only about one-quarter of electrical and mechanical engineering graduates have remained past 40 years of age in purely technical engineering work, involving practically no executive responsibility.
3. The rest, or roughly one-quarter, have gone ultimately into work such as teaching, selling and consulting, all of which involve dealing with people.

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1. For references see Bibliography.

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4. Those who have gone into work involving executive responsibility (group 1) have, on the whole, received greater financial reward than those in group (2) whose work has not involved such responsibility.

5. Those in *general* management, specified in (1b), whose duties have been entirely administrative and practically non-technical, have, on the whole, received much greater financial reward than any other group.

Three extremely important facts of general knowledge might be added.

6. Practically all college graduates, whether engineers or not, who have become successful in management, have learned all they have known about it, in practise. Formal college training in management, in the general sense, has existed only during recent years, and in only a few institutions. But it is steadily increasing.

7. Practically all engineering graduates, whether they have gone into some form of management or not, have encountered those human relations which are inevitable in the cooperative enterprises in which engineers engage.

8. The great technological progress of the last half century has been based, first, upon the extension of scientific knowledge by scientists; second, upon the careful and rational application of this knowledge to the solution of practical problems by engineers; and, third, upon the organization of capital, physical facilities, and men for production and distribution, by those in management.

Retrospect

Industrial management and engineering are twin brothers; they have developed together. With a constantly expanding science and a growing army of engineers and inventors who applied that science, American industry has developed from the simple English patterns of the 18th century to its modern, gigantic, highly organized branches, all of them interdependent, capable of turning out with incredible rapidity and perfection steam turbines, electric generators and motors, automobiles, radio sets, cigarettes and plastic products. During this development, both industrial management and engineering naturally experienced a correspondingly extensive metamorphosis. The range in responsibility and in requisite talent, ability, and knowledge was multiplied a thousand fold. This extension of industry was upwards, fan-like. The small factories and machine shops continued, but there was also tremendous growth both in size of organizations and in range of products in the expanding industries. This two-way growth necessarily demanded not only a commensurate increase in level of ability to handle merely the larger and consequently more complex management problems, but also a corresponding increase in technical knowledge and skill, on account of the ever widening spread in range of manufacturing processes and of products, from the simplest, well-understood forms to the most technical and complicated. In this expanding industry, including even those branches of non-technical character, the problems of both management and engineering called for less and less guess work, and more and more rational treatment.

Under these conditions of growth, the thing which might have been expected, happened. Practically all of the conditions were favorable for the engineer to be called to management positions. He was geographically on the job; his distinguishing characteristics—a scientific attitude of mind and method of approach—were among the foremost requisites, and, moreover, he was vitally interested, because he not only understood the processes and the products, they were his creations! Hence by normal growth and evolution many engineers have come into administrative positions.

What has been the past relation of education to management? To what extent has engineering training been appropriate and adequate for management; to what extent, essential? Formal college training in industrial management is of recent origin, and hence has had very little, if any, influence in determining the present personnel in management. On the other hand, the character of engineering education undoubtedly has influenced it. How much, relative to the influence of other existing forms of education, is not altogether clear. For instance, whether the number of engineering graduates engaged in industrial management, considered in its most exclusive sense, is a larger percentage of all engineering graduates than the corresponding figure for graduates of other courses, is not definitely known to the author. But that there are large numbers of the latter in industrial management is a well-known fact, and this should not be lightly dismissed in any comprehensive review of the relation of education to management. However, it is certain that a large percentage of engineering graduates are in industrial management positions of one form or another, and particularly in both those which require technical knowledge, and those which, although not requiring such knowledge, are more or less terminal positions from a line or promotion through the former. There are, of course, thousands of positions of these kinds in industry, and for these, certainly, engineering training has been, at least in part, a logical preparation. Its lacking elements have been the subject of many an utterance; and unquestionably essential phases of management—such as personnel and accounting, for instance—have been omitted. Yet it is also an indubitable fact that, quite consistent with his characteristic quality of finding out how to handle new problems, the engineer has acquainted himself, at least to a practical extent, with these other phases, and has done the job. How appropriate engineering training has been for those management positions for which technical knowledge *per se* has not been a requisite, either directly, or as a stepping stone, is largely a matter of opinion. Only this is certain: to the extent to which a quantitative method and a scientific attitude and approach are requisite or desirable in management, engineering training is highly appropriate. These qualities do seem desirable, and in the larger industries, requisite. The engineer's sequence of training and progress has been perhaps not as well ordered as it might have been, nor as it should be in the future. However, the point is that in that particular

stage of industrial and educational development, it was a logical outgrowth, and it worked, as is attested by the growth of American industry.

In relatively recent years there has been a growing recognition in the educational policy of engineering colleges, of the all-pervading fact that the majority of engineering graduates have gravitated ultimately to some form of management. This recognition has largely taken the form of adding appropriate electives to the regular engineering curriculum, and in setting up new courses under such headings as industrial engineering, engineering administration, etc., in which the essential core has been engineering. This has been in accordance with the recommendations both of the Mann Report and of the S.P.E.E.

But there has also been a rapidly growing philosophy which would not recognize the essentiality of *technical engineering* subject matter in college preparation for general industrial management. It holds that a scientific attitude and rational method of analysis, which are recognized both as essential and also as characteristics of engineers who have succeeded in management, can be developed on some other subject matter than engineering. This general idea has not yet, to the writer's knowledge, taken full-fledged practical form, unless some of the business administration courses are so regarded; but it is being reflected in the gradual deletion of technical engineering matter from such courses as mentioned above, and the substitution of general management studies. So the presumably more direct and certainly less exacting college approach to management is gradually being set up.

The financial reward for technical leadership has been less than that for general managerial leadership. According to the statistics, the man who has been able to "run" things—to coordinate human activities effectively and to judge soundly, toward definite objectives—has been valued more highly by leading executives than the man whose natural talents have been in a technical vein. Moreover, according to the facts, even those who could manage men and things in technical activity have received less financial reward than those in "general" management, in which technical engineering knowledge *per se* is either not essential or is altogether secondary. Going still further, those who have remained in purely technical work with no executive responsibility, have been the most poorly paid. On the face of it, then, it would appear that in some fundamental way, mere association with technical matters relegates one to a lower stratum in financial reward.

However, that it has been so in the past should not be accepted as the establishment of an eternal fact. Random play of tremendous forces out of equilibrium have been the order of the day, and we must be wary in drawing conclusions from experience of such a character. But the clear implication is that something is wrong; technical engineering leadership has played too important a part in the past and obviously will be too much needed in the future, to be now overlooked and smothered into insignificance under our intense enthusiasm for industrial management, which it largely created. It is not a question of merely giving such leadership its due; simply we should be stupid trustees, indeed, to the next generation if we created a problem for it by letting the present trend slip ahead unabated. Our first problem in this connection is to try to understand the past better. It is complex enough, but a thoughtful review does indicate, here and there, a rational thread running through it all.

Supply and demand, as it relates to the present subject, seems to be one such thread. In the mad rush ahead, there has been a greater relative scarcity of managers, for whom no formal college training facilities had existed, than for technical leaders, for whom such facilities had been abundant. But scarcity for that reason, it should be observed, was only an accident; it was not a scarcity of natural management talent. The apparent result has been that much, but fortunately not all, of the best engineering brains necessarily has been conscripted for difficult service as pilots through these new and uncharted management areas. Thus the pressing and urgent demand during this industrial development era for men to fill administrative positions, dug deep into the upper levels of engineering ranks.

If much of the best brains turned to management, and, moreover, if there yet continued to be a scarcity of management ability, it is not at all surprising that this should be reflected in financial reward. By and large, if those who entered management could do the technical work the others were doing and were also capable of managing, were they not more valuable? Undoubtedly; to the extent that this was so. If they were better all-round men, naturally they could earn more.

On the other hand, the group of engineers who have remained in purely technical work—comprising about one-quarter of all engineering graduates—have been poorly paid relative to all others. This can probably be justified. What is the function of those who remain in purely technical activity, with no administrative responsibility whatever, and who are not technical leaders in the above sense? Routine technical activity. They have learned how to make certain routine calculations, drawings or tests, or to operate some machinery, and they do these things day after day in a routine and satisfactory manner. Their work is important—indeed the execution of such tasks is obviously essential. The point is that a four-year college education is hardly a necessary prerequisite to such tasks. Those who have remained in such positions are, for the most part, those who have not possessed the requisite qualities of a successful engineer; and doing the work merely of a trained technician, they have been paid accordingly.

However, there is one element in this financial reward matter which does not fit in so well. *Creative*, technical engineering *leadership* has not been appropriately rewarded. There are two sides of technical leadership.

One is technical management, which administers the day-to-day technical processes of operation, design or calculation. The other is *creative,* professional leadership in technical matters. In this leadership is that small group of 10 per cent or so of scientists and engineers who are identified by *creative achievement.* They are the ones who conceive the new technical possibilities—who can see through the technical mists which blind most of us; who thus provide the radically new concepts and methods, whether they be new forms of machines or structures, new ways of building these, or new principles and methods of predicting performance. These things are absolutely indispensable to technological progress, in the same sense that the products of creative, professional leadership in management are absolutely indispensable. One whose head is a fountain of *creative* ideas is thus a technical leader, even if he cannot himself do much toward putting them into practical or material form. If he can, he is simply that much more valuable as a leader. The one quality rounds out and supplements the other. Either may predominate in equally valuable men—valuable as measured in terms of achieved results. Both functions are professional in character and are complementary in relation to each other, and should therefore be regarded more nearly on the same basis so far as reward is concerned than they have been. It is a matter of fairly general knowledge, which the surveys have confirmed, that this phase of technical engineering leadership has not been, on the whole, appropriately rewarded. This state of things in which commensurable achievements are not weighed in the same scales does not fit well into any rational picture. Emerson said, "Money, which represents the prose of life, and which is hardly spoken of in parlors without an apology, is, in its effects and laws, as beautiful as roses. Property keeps the accounts of the world, and is always moral. The property will be found where the labor, the wisdom and the virtue have been." One wonders where he got his data.

However, there is a very definite, favorable trend in policy about these matters in some of the large industries, even if this is not reflected in the surveys; so there are indications that creative, technical engineering leadership is beginning to approach its proper estate. But one wishes to see this favorable trend spread about more rapidly.

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Thus looking back over the development of industry with the purpose of understanding the relation which has grown up between engineering and management, one discerns among other things, that the reason why engineers have trended in such numbers toward positions of administrative responsibilities in industry is not alone that they acquired technical knowledge at college. This, of course, has had its important influence, but the things which seem to have had a predominating influence are: (1) a pressing demand for managers in the rapidly growing industry; (2) the absence of any source of graduates formally trained in the fundamentals of management; (3) engineering graduates have possessed one of the requisite qualities of capable management—a scientific and utilitarian attitude of mind and an analytical method—even if their formal college training has lacked almost completely any consideration of the fundamental aspects of management; (4) they have been directly interested, geographically on the job and thus readily available; and, of outstanding importance, (5) they have been resourceful and able to acquire in one way or another, the necessary additional knowledge and ability for adapting themselves successfully to management.

One sees, in addition, an extremely wide range in industry, from the highly technical, on the one hand, to the practically non-technical, on the other; and consequently a correspondingly wide spread in the technical educational requirements for management throughout the range.

And finally, one finds that financial reward has been distributed in a reasonably rational way, with one glaring exception. It seems reasonable that engineers at the top in general management should receive higher reward than those at the top in technical management, and so on down the line; and that those in technical management should receive more than those in routine technical activity. But it does not seem reasonable that creative, technical leadership has not ranked more nearly on a par, throughout the range, with creative, managerial leadership. This, coupled with the creation of attractive courses leading presumably more directly to management, is rapidly removing incentive for the best minds to take technical engineering courses.

Looking to the Future

When we orient ourselves in the direction of present trends and follow out those few clearly discernible lines from the past, they seem to lead to certain fairly definite indications. The foremost of these is that the future will have no less need than the past for leadership both in the scientific and technical fields of engineering and in management. On the contrary, the need will probably be greater; everything is getting more complex; each year it is becoming more difficult to see from one end to the other of this growing, technical-economic-social crazy-quilt with such thousands of complicated, overlapping and changing patterns. Trained minds *for leadership* will be all the more essential. Inventors must more and more have advanced scientific knowledge; the cream of invention has already been skimmed from the more obvious aspects of science, and therefore inventions will unquestionably become, in increasing measure, the product of scientists and engineers. The real leaders in technical engineering must also be more thoroughly trained in the basic sciences and in the rational applications of scientific principles to practical problems. Moreover, they must have a better compre-

hension of the human aspects of their job; they must learn to deal more effectively with other people, for it is a part of their job. And leadership in industrial management must likewise become broader in its outlook, more scientific in its knowledge and more rational in its approach to general management problems. In a word, all professional leadership—not excluding law, banking, the clergy and the rest—must broaden its outlook, perennially develop its scientific base and improve its art; else, in the inexorable advance of complexity, the leaders will become even less able than they are now to see across the boundaries. We have all taken hold of the technological bull's tail, and it is too late to let go; instead we've got to plan pretty quickly how to guide this brainless, powerful brute toward a rational objective, or he will distribute us prostrate over the terrain.

Another indication is that the same forces which have moved engineers into management will continue to do so, in a somewhat modified form, in the future. Much of the industry will continue to be based upon engineering; and with this and its collateral conditions remaining, that movement will undoubtedly persist, but with modifications in two respects. In the first place it will probably be modified by the influx of a new group which has not existed during the past growth of industry, namely, college graduates who have had formal training in the fundamentals of general management, but who have had little, if any, technical engineering training. With the very wide spread of industry itself and of function within the larger industries, it is practically certain that such graduates, who will not be engineers, will be absorbed in those areas of industrial management where technical *knowledge* is not essential. Then also there will be the graduates of those existing courses which, although still designated as "engineering"—in most cases properly so—are yet intended primarily as fundamental preparation for industrial management. Altogether then, there will probably be a very large body of graduates, most of them falling under the heading of engineers, who will be available, alongside technical engineering graduates, for industrial management positions. The flow of technical engineering graduates to management will therefore probably be modified both by the withdrawal from technical courses of managerial-minded students, and by a competition after graduation which has not formerly existed; to what extent, will depend upon whether such management courses have successfully retained those elements which engender the method and attitude that have been characteristic of engineers, and which presumably have been the keynote of their success in management.

If such elements are retained, then there seems to be no reason why in the future those other graduates should not comprise a large percentage of those in management. The tremendously wide range in type of industry surely affords openings in management for men of all degrees of technical training. Even in the most technical industries there are many administrative positions which require only a very limited technical knowledge; and the further up one looks in the organization, the more this seems to be so. Take the General Electric Company for instance. A former president and a chairman was a non-technical man from the shoe industry; the present chairman is a lawyer by profession; there has always been a large fraction of its administrative officers who were not technical men; and many of them, including some who were technical engineering graduates, joined the organization in middle life. All of this has evidently reflected a wise policy, if a successful organization is any criterion; but the point to be illustrated is that technical engineering graduates are not altogether essential in the *general* management of a highly technical industry. Hence, if the colleges do a good job, it seems practically certain that, within another generation, graduates of engineering-management and other less technical courses will figure heavily in industrial management.

However, there is one point to be kept in mind. There should be at least some individuals in the high levels of general management who have an understanding and appreciation of technical matters and a sympathetic interest in research. The half-informed business executive who disparagingly avers that he can get all the engineers he needs at $40 per week, or who naively believes that creative processes can be put on a mass production basis, is a misfit in modern industry. Such views, fortunately, are gradually passing. There should be general management leadership which thoroughly understands and has a sympathetic interest in technical progress. This can come most effectively from former technical leaders.

What is the future for technical engineering graduates? Are they doomed? Not at all. On the contrary, their estate should become as attractive as any, if industry and the colleges adopt wise policies. There are two important phases of management which will indubitably be reserved almost exclusively for them; and, in addition, all other fields will be open to them just as they have been in the past, except that the competition will be more keen. One reserved field is technical administration which has always served as a stepping stone to higher levels. The other, and altogether foremost, is the creative, professional guidance and administration of technical and scientific progress. In this, which obviously is one of the most important management functions in society, one must be capable not only of creative technical leadership, as already discussed, but, in addition, be able to guide and manage others; in other words, be capable of management in a dignified and highly select field. And in this field also will be those technical and scientific leaders who may not be capable of management in its strict sense. These fields afford broad and extensive professional opportunities for technical engineering graduates; and adding to these fields the opportunity, as in the past, to enter any other phase of management, the future possibilities for

such graduates can be highly promising. They may be in the minority in general management, but they will be adequately represented there, and, if all goes well, will also be in other enviable positions.

Thus looking to the future, the indications are that there will be even greater need than in the past for trained professional leadership in all fields. The same forces which have moved technical engineers into management will continue, but will be modified both by the withdrawal of managerial-minded students from technical courses and by the influx of graduates of engineering-management and other courses designed primarily as preparation for management. The latter graduates may preponderate in numbers, if proper elements are maintained in their college programs and the general estate of technical engineering graduates can be, and, in the interest of balanced progress should be, made as attractive as any.

Future Policy

Educational policy cannot be logically separated from industrial policy; there are too many respects in which they are tied together. Most engineering graduates enter industry of one form or another, hence engineering colleges have always taken into account the requirements of the industrial job. When industry wanted graduates who were "practical," the colleges built work shops and tried to make their courses practical; when it changed its mind and insisted rather upon more "fundamentals," they gradually swung in this direction; and when it put large numbers of engineers into management, they worked out courses which would be preparatory to management. Thus any rational educational policy must give appropriate recognition to this interlocking of interests between the industries and colleges.

Moreover, an educational policy which did not recognize the often expressed hope that the engineer might sooner or later take an active interest in those unsolved, complex, social and economic problems which his technology has largely created, would surely be inadequate. What should that recognition be? Sociology, industrial history, and more economics? Undoubtedly this would be valuable to him if he later took such an active interest; but those engineering graduates who have gone into business, banking, management, etc., have not done so because they have studied these subjects in college; forces of circumstance and, above all, a special type of qualification have combined to move them there. And in all probability if the engineer ever takes an effective hand in the solution of such social problems, it will not be because he studied subjects relating to them as a major part of his curriculum; for if he did, he wouldn't be an engineer. Something more must be expected from education—more than merely providing in addition to engineering, a proper balance of courses in sociology, industrial history, and the like. It must make such courses stimulating and distinctly purposeful. If they are successful in *starting* the engineer to read and to think about such matters with purpose, so that after graduation he will continue and thus acquire a full appreciation of human and economic values, then, in the writer's opinion, education will have done all it can do, but nothing more than it should do.

Another thought which should be stated at this point relates to the scope of activity which may be properly classified as engineering. The practise of engineering has *demanded* straight thinking and an unqualified respect for facts. The engineer can find no shelter under an alibi. His responsibility is ruthlessly definite. He has thus been obliged to exhaust every resource of science, all technical knowledge and every power of rational analysis at his command, in order to feel confident that his designs and predictions were sound. He has not done this by virtue of an extraordinary wisdom of a biologically unique group of individuals; he has simply had to do it in order to endure, and in a sense and to a degree that most members of other professions have not. Consequently not as many of them have become so skilled in scientific method. He deserves great credit both for his achievements and his methods, but in the interest of keeping our educational feet on the ground and without detracting at all from his achievements, let us recognize the special circumstances which have given rise to his distinguishing characteristics. Otherwise, our inferences may not be sound.

We may conclude that such characteristics cannot be developed by other professions; that engineering is the proper training for management, business, finance *et al*; and also that engineering graduates who are successful in these other fields are still practising engineering. Thus engineering would come to mean everything which is done thoughtfully, and would therefore mean nothing. Let us keep engineering as engineering; have pride, of course, in those engineering graduates who become successful in other professional fields, and perhaps trust that by their examples these other professions may be graced and benefited; however, when it comes to education, let us not be too presumptuous in our advice to other professions; let their schools introduce engineering content or method in their curricula if they wish to do so, but let us not try to stretch the engineering curriculum over the whole domain.

It has already been stretched to the breaking point in its affiliation with management. Here we have a perfectly legitimate reason for extension; many phases of the management of engineering enterprises logically can be, and certainly are, regarded as engineering. But as we approach general management, the engineering aspects gradually diminish, and in the limit, engineering *per se* has vanished. An engineer may be on the *general* management job using methods and habits of mind he acquired in engineering practise; but he is no more practising engineering, as the writer conceives it, than

is his brother engineer who went into banking; or than the lawyer who went into management is practising law. The one is still an engineer, and the other still a lawyer; but their new function is neither engineering nor law. It is general management.

* * * * *

Some general observations should now be stated regarding college educational process, as the writer views it. This is venturesome, because he is not qualified as either a professional educationist or psychologist, and may therefore violate technical terminology and perhaps more; but it seems necessary, for the purpose in hand, to state in a layman's terms the more or less distinct phases of educational process as they appear to him. There are thus five phases, as follows:

1. The first relates to the process of acquiring factual and definitive knowledge. One learns for instance, the factors in the "flexure" formula in mechanics; the *definition* of "marginal utility"; that Disraeli was an English statesman; that the base of napierian logarithms is 2.718; that inertial reaction = mass × acceleration. It is the process of building up one's mental encyclopedia. It is essentially a memory matter.

2. The second has to do with that type of reasoning in which the student is *led*, step by step, through logical processes either by a teacher, or by a text book. His part in this particular phase of his journey through the educational forest is not to move precariously along a trail which is only blazed; instead he rides on an educational sight-seeing bus over a modern, concrete highway of which even the curves and grades are reduced to a minimum. His only responsibility is to take due note of the scenery, and of the announcer's comments as he rides along. For instance, he may be thus escorted through the *logical development* of the "flexure" formula; of the *theory* of "marginal utility," or of the vector representation of alternating currents. This process is one of civilization's necessary short-cuts. In order to reach the frontier of new things, to acquire on the way an acquaintance with the methods used there, and yet have a reasonable portion of one's life still available for professional activity, some such rapid transportation seems absolutely necessary. In the process one learns to follow logically and to retrace the steps; one's mental muscles are developed somewhat, but they do not become sturdy and of good form by purposeful exercise under their own power; instead, they are massaged.

3. The third phase is the process of acquiring skill in manipulation. For example, one develops skill in algebraic transformations; in numerical calculation from formulas by the slide rule; in operating a machine; or in carrying out an experiment. It is a discipline in procedure.

4. The fourth phase relates to that type of reasoning in which the student himself takes the initiative. *He* establishes the trail. The objective may, at first, be defined for him, and perhaps its general direction and a few landmarks may be indicated; but he presses through alone. In clearing away the undergrowth, in fording or swimming the technical streams which cross his path, in retracing his steps for a new start when he encounters an impasse, he not only exercises his mental muscles in worthy activity and stretches them to the elastic limit, but also develops his sense of direction and his power of discerning helpful landmarks. Each successive trail thus established *by him* increases his pioneering powers; and presently he will be able, if it is in him, to blaze his own trail through new areas to new objectives. The S.P.E.E. Report says:

> A besetting danger in engineering education is that our effort to maintain a high standard of work, if misdirected, may lead us to prefer efficient routine to less certain but more educative self-directed effort.

5. The fifth has to do with the establishment of a natural continuity between the development of the individual at college and after college. The branches of a truly educational program will neither terminate in dead ends here and there during the college course, nor be chopped off at graduation. Instead, they will feed *primary educational stems* which will both continue and expand beyond graduation as long as the individual is on the ascending slope of his professional career. However, the extension of such stems after graduation is extremely difficult unless the student has already begun to extend them under his own steam before graduation. He must develop under guidance both the *desire* and *power* to extend them. The college can plan them and give him guidance; but *he* has to develop them. He cannot be expected to do this unless his course work is definitely planned with this general idea in mind; unless the idea receive continued emphasis, especially in the last two years, by repeated reference to the relation between his present studies and those which he will pursue after graduation. This means, then, first of all, a competent leader as a teacher; and secondly, not only a well balanced curriculum for the purpose, but, in addition, a plan obvious to the student, according to which every branch of study feeds one of the general educational stems which are to project and expand beyond graduation.

The underlying thought here is clearly recognized in the S.P.E.E. report:

> Money costs, the mating instinct and the time demanded for making adjustment to practical life, tend to set a time limit to education as a formal, scholastic process and to push a growing and important part of it over into the early years of productive life. This principle should be frankly accepted in engineering education by recognition of the fact that the process is divided into scholastic and post-scholastic stages.
>
> In this connection we would reaffirm our view that the proper time for specialization is after the undergraduate course, and that in a majority of cases specialization must accompany active experience rather than take the form of a further discipline in college. The provision of effective continuation education for this period remains one of our most urgent problems.

The great importance of establishing such educational stems, however, seems to the writer to demand much greater emphasis and definite planning.

Of the foregoing five phases, probably the first three are essential in the preparation for engineering work of any character; they are sufficient, it would seem, for *routine* technical activity, but the last two, in addition, are absolutely essential to progress toward any highly *professional* goal. If they are omitted at college, as they largely are, the graduate is obliged to provide them somehow after graduation, or else not reach the goal. It is probably a fair statement that not one out of twenty-five students is consciously forming an organic educational structure in his mind, as outlined in phase 5. They think that purposeful study and reading normally end at graduation. To correct this situation—to provide phases 4 and 5—is, in the writer's opinion, the foremost problem confronting pre-professional education. This is particularly so in engineering and management courses, because, unlike law and medicine, students have, as a rule, only four years of formal training.

The specific numbering of these five phases is not intended to imply that they should normally follow each other in practise in that order. On the contrary, they should largely run parallel.

Turning more specifically to the engineering-management aspects of educational policy, those students who would come within the scope of our subject can be classified, for the purpose here, under four divisions according both to natural qualifications and to appropriate education. It may still be very difficult practically to identify these groups completely, but they exist nevertheless, and every effort should be made to learn better to identify them. They are as follows:

Sub-Professional Group. Those who are primarily qualified by nature to carry out assigned tasks, either in technical work or in routine supervision. These comprise certainly one-half, probably more, of all college students which come under the scope of our subject. They comprise not only those whose intellectual qualifications limit them to such activities, but also those who don't want to do anything else. There are people of high intellectual ability who shrink from responsibility of any kind, or who are misfits, or who are plain lazy. They all seem to share a common level of activity with those who can't do more.

In accordance with the S.P.E.E. recommendations,[10] the educational program for this group, excepting the misfits and the lazy ones, should be that of the technical institute, which recognizes primarily the first three phases.

Professional General Management Group. Those who have outstanding natural powers of leadership and understanding, but relatively little technical leaning. This group may be expected to fill a portion of those positions of industrial and business administration—*i.e.*, general management—which do not require technical knowledge.

Just what their educational program should be is a question which is largely outside the writer's knowledge. However, they must be well educated men of reasonable culture; hence it is safe to say that there should be at least two—possibly three—stems: a cultural, and a social and economic, and possibly a slim technical one. The experiment of training men directly for general management is an interesting one, and should be encouraged. One great danger to be guarded against, of course, is the idea in student's minds that such a course provides the "royal road" to general manager or president. Moreover, if the experiment is not successful, it will certainly not be because there were no industrial positions which did not require technical engineering knowledge; it will be because such courses either were not successful with their materials, as engineering courses have been with theirs, in developing a scientific attitude of mind and method of approach; or because the fundamental point was overlooked that most of the professional aspects of management have to be learned on the job.

Professional Engineering Group. Those who have outstanding natural talents along technical lines, some of whom have, in addition, the natural qualities of human leadership. From this group we should expect the future technical leaders; to some degree, leaders in general management, and, possibly also a few who would become actively interested in the larger social and economic problems.

Their program at college should have three stems—one main and two auxiliary: technical, cultural, and social and economic. The first and main stem should be a rigorous and thorough technical discipline. It should recognize all five phases, and should be framed around the basic engineering "core" referred to in the Mann Report, the S.P.E.E. Report and more recently by Dean Kimball;[11] it should lay more emphasis upon the interpretation of fundamental physical laws and their application to the solution of illustrative problems than upon the memorization and use of standard formulas in connection with type form cases; it should continually consolidate the gains achieved in all branches, by feeding them into the main educational stem. For instance, in the junior and senior years it should make use of the results achieved in mathematics, physics and mechanics, not in separate problems in as many classifications, but in engineering problems involving all. Past achievement would thus be unified with respect to the main purpose.

The cultural stem necessarily must be slim. But it can be vital, and should be so. Perhaps the most that can be expected in the brief time available is to emphasize not only the technique of speech and writing (phase 3), but also and principally the fundamental purpose of most speech and writing—namely, to clearly express an idea—and the importance of this in professional life; and to *engender the habit and desire* of purposeful reading of historical, philosophical and other

cultural literature (phase 5). In the writer's opinion, this has not been sufficiently emphasized in the reports referred to.

While the social and economic stem is like the cultural in two respects, it is nevertheless of relatively greater importance. It is like the latter both in that it is auxiliary in character and that the general educational purpose is the same, *i.e.*, gradually to establish, in accordance with phase 5, the habit and desire of reading and thinking in a given field. In this case, however, it is about such practically important matters as industrial history, human relations in industry, sociology and economics of engineering industry and business. Taking courses in such subjects and letting it go at that is not enough; it must all be purposeful.

The program for the *professional engineering group* also should anticipate that a moderate fraction of them will take formal post-graduate work either in college or in industry.

Professional Engineering-Management Group. Those all-round, capable men who have a definite technical leaning and also the natural qualities of leadership. This group, after graduation, may be expected to pass along the industrial, three-stage separator in which the first stage comprises the lower and moderate levels of technical activity; the second, technical management; and the third general management. Each stage will take its toll of men. And again, one would hope that some of these would ultimately become interested in general social and economic problems.

Their college program, like that of the *professional engineering group*, should have three stems—the same three stems; but there should be a fundamental shift in emphasis in two of them. This group should develop and retain the engineer's attitude and his respect for quantitative facts and measurements, both because that attitude and respect will always be highly useful, and also because technical engineering practise will presumably constitute his entree to management responsibilities. However, the latter, being the main objective, should be given a corresponding weight in the program. Thus the social and economic stem should, it seems, receive the same relative weight as the technical stem for the professional engineering group. The technical, for the present group, should lay relatively greater emphasis on the first two phases; the social and economic, on the last two phases. Analytical and pioneering powers should be exercised heavily on the subject matter of the social and economic stem, so that this will have a vital growth after graduation. For illustration, take human relations in industry. Can you teach in undergraduate courses the professional technique of personnel management, or the art of getting along with associates? It would seem to be quite hopeless. But you can introduce the student to fundamentals, and exercise his analytical powers on actual personnel problems—all with the idea of developing a purposeful and enduring interest, and, as Professor E. D. Smith says,[12] of making him "sensitive" to the lessons of experience.

The cultural stem should presumably be the same as that for the *engineering group.*

Summary

During the development of industry, engineering and industrial management have evolved together. Certain phases of management, as the writer views it, have actually been a part of engineering; others have not. The direct administration of technical engineering activities *is* engineering, in the same sense that the administration of personnel and procedure in a legal matter is law. However, we should not become confused; the further movement of engineers from such technical management to general management has not made the latter become engineering, any more than the movement of numerous lawyers also into general management has made it become law. It is still general management. Engineering and management are thus closely related, but all management is not engineering.

Looking to the past, the facts are that something over a quarter of engineering graduates have gone into general management; a quarter have remained in technical management, which is engineering; a quarter, in purely technical activity; and the rest in sales, consulting, teaching, etc. Those who have gone into general management have received the greatest financial reward; those who have remained in purely technical activity, the least.

Looking to the future, it appears that, on account of the rapidly increasing complexity on all sides, even more capable leadership, both technical and managerial, must be provided for the future. It seems clear also that the forces which have moved engineers in such large numbers into positions of executive responsibility—both technical and general—will continue in the future. In other words, technical engineering graduates, it appears, will have the same opportunity as in the past for movement into such positions, excepting that they will be in competition with graduates of courses designed as fundamental preparation for executive positions. There is a very real danger that both the prospect of a greater financial reward, and the less exacting nature of these presumably more direct courses in preparation for management, will cause many to turn from technical engineering courses who are naturally qualified for such work, and who will be needed for technical leadership in the next generation. The problem of financial reward is one which the college cannot solve; industry must do it, not alone to give creative, technical leadership its due, but, in industry's own interest, to prevent the source of technological progress from drying up.

For the purpose of defining educational policy, the students who fall within the scope of our subject can be broken down into four divisions: a *sub-professional* group, and three professional groups, namely, *engineering, engineering-management,* and *general management.* The educational program for the sub-professional group should be that of the technical institute. It should recognize primarily the first three phases of educational

process—the acquisition of factual and definitive knowledge; the development of technique in manipulation and procedure; and the understanding of basic theory. The programs for the professional groups, on the other hand, should recognize all five phases, and should emphasize particularly the last two—*viz.*, the exercise of analytical and pioneering powers; and the development of *primary educational stems*, and of the power and desire to extend and expand them after graduation. It is around these stems that the results of purposeful study and experience will be structurally articulated. The professional groups, it seems, should all have the same three stems: (1) cultural, (2) social and economic, and (3) technical. Merely the emphasis would be appropriately different.

The present inability completely to classify all students according to natural aptitudes should not discourage us. Such a classification is now possible to a limited degree. In any case *a* division is made; boys actually do choose to be engineers, lawyers, managers, etc., and college courses are set up to train them. A rational solution of the educational problem, it seems, can be approached only as we learn progressively to sift out types during the lower educational stages, and somehow help the individuals to find their way into educational programs and activities along the lines of their natural aptitudes.

In a summary word, let us recognize the necessity of providing appropriate educational preparation for industrial management; but in our enthusiasm for this, let us not misinterpret past experience and thus fail to recognize another equal necessity; we must also provide both an appropriate educational preparation and a promising outlook for technical engineering leadership. Its contributions to technological progress surely bespeak a greater recognition than it has had. But mere justice is not the point here. It is a question whether, by a stupid perversion of emphasis now, we shall encumber the next industrial generation with the problem of a dried up source of technical engineering leadership. Wide publicity of the new facts regarding attractive salaries in management, and the continued establishment—proper as this may be—of less exacting courses leading to management, will, it seems, inevitably discourage the more capable men from choosing technical engineering courses. The solution is not to suppress the facts or to discourage management courses, but for industry to recognize the situation, as some are beginning to do, and appropriately reward technical engineering leadership; in other words, to make such leadership a worthy and promising goal on its own score, and not merely as an entree to general management.

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Discussion

R. E. Hellmund: The study by Professor Doherty of the educational aspects of engineering and management brings out a great many very interesting facts and conclusions, practically all of which coincide closely with my own experience and observations in my work with the Westinghouse Electric and Manufacturing Company. I wish to emphasize in particular the point that our enthusiasm over the fact that in the past our engineering education has turned out personnel suitable for industrial management should in no way lead to a diminution of the engineering phase of the undergraduate program in an attempt to provide at the same time the education necessary for managerial work. Undoubtedly the undergraduate program should have the three stems mentioned in the paper; namely, technical, cultural, and social and economic, and I am confident that no mistake will be made in always placing the main emphasis on the technical phase and giving merely enough of the cultural and social and economic to arouse the interest of the students in these subject matters. The fact that only 25 per cent of the engineering graduates remain in purely technical work after the age of forty should not result in our overlooking the fact that by far the majority of all students during their earlier life, and especially, soon after leaving college, are called upon to carry on technical engineering; as a matter of fact, the greater part of all engineering work, not only of the routine type but also in the more progressive and advanced lines, is done by men during their early professional life. It would therefore be a great mistake and likely to reflect very unfavorably upon the quality of engineering and the technical progress made if the technical subjects of the educational program for engineers were reduced below a certain necessary standard.

The previous remarks should by no means be taken as indicating that industry is not badly in need of leaders and managerial talent and that educational programs should not take this into account. However, in so far as all those men who eventually work toward advanced and managerial positions usually carry on postgraduate work, either in college or otherwise, the emphasis on studies necessary for these positions should be left for such

postgraduate work and as preparation for further advancement in industrial life. The student after entering industrial life will have a much keener appreciation of psychological and business problems than can be had in college. Furthermore, he will be in a better position by that time to sense whether his natural aptitude is toward purely technical or managerial work and will be more able to choose between the various studies suitable for either phase of the profession. I would therefore advocate that, rather than materially changing the undergraduate courses, considerable attention be given to the training of personnel for managerial work during the various postgraduate programs and to inducing a certain number of engineers to emphasize this part of the work during their postgraduate education.

D. C. Jackson, Jr.: Professor Doherty brings out that the really able men in engineering work in the industries are brought into management because of their ability and he suggests that the greater financial return accruing to these men, especially those in *general* management, is due to the fact that they are in management as such. In following the progress of able engineers in the industries during the past ten years, my opinion has come to be that it is not management *per se* which brings the larger remuneration, but the fact that men of outstanding ability in general and broad fields of endeavor are more necessary in management than in purely technical work. As a result, the able men who are given managerial duties receive higher salaries because of their ability which gives them increased value to the industry, rather than merely because they are in management instead of purely technical work.

Professor Doherty is correct in saying that the engineer in management work is still an engineer and continues to have the engineering trend of thought and to solve the problems he encounters with the logical and keen method of analysis which he has acquired in his engineering training and practise, but that such an engineer is not doing engineering work. A man doing work of this sort is still an engineer, although he is no longer actually in the field of engineering. It is this fact that has made the engineer particularly valuable in the industries (and in this term I include the public utilities, railroads, etc., as well as the manufacturing establishments which are frequently classed as the "industries"). It is my belief that engineering training will continue in the future to be valuable to men having managerial duties in the industries based on engineering. There may for a time be a trend of students toward courses of business or engineering administration or management which will carry some of our abler students away from the undergraduate engineering courses. However it is doubtful whether such courses of study can provide as satisfactory a training as do engineering courses in the "straight thinking and unqualified respect for facts" combined with logical analysis, all of which are so desirable and necessary in our present-day industries. It is my confident belief, if the engineering educators continue as progressive as they have in the past in eagerly making the engineering training particularly effective in the solution of modern problems, without sacrificing the sound principles fundamental to engineering, that the engineer will prove in the future to be even more valuable in both engineering and general management.

Ernest E. Johnson: I should like to present evidence of one point which Professor Doherty has made in his paper, namely, that in industry, men for responsible engineering management positions are and can be drawn quite largely from among those who have made substantial success at technical work.

For the past ten years I have been with the General Electric Company at Schenectady, seven years of which have been spent in connection with personnel and educational activities. I have seen it happen time and again that men who have demonstrated a high order of technical leadership have gradually come into positions of technical management by that route.

One man who was very successful in the technical design and development of mechanical devices is now engineer-in-charge of the Welding Engineering Department and is chairman of all welding activities for the entire company, an activity involving several millions of dollars annually.

Another man who demonstrated exceptional ability in the highest type of analytical engineering work was placed in charge of directing a group of ten or twelve men engaged in power system studies.

Another, a first-class designing engineer, is now in responsible charge of an engineering organization at Lynn, Mass., for the design of turbo-alternators.

Still another, of high talent in general engineering, has been placed in the manufacturing department at Schenectady in charge of waste and spoilage—an activity which calls for high leadership and which involves all of the manufacturing divisions at the Schenectady plant.

And there are many other cases. From this experience and from my frequently having acted as a buffer between over-zealous department heads on the one hand and the outstanding young men on the other, to prevent the latter from leaving technical leadership for technical management too early, it is quite evident to me at least, that there need be no fear that we will be taking away from the field of management by including in our engineering curricula a fundamental technical background.

I—Combined Reliability and Economy in Operation of Large Electric Systems

THE DETROIT EDISON COMPANY

BY A. P. FUGILL*
Member, A.I.E.E.

With but few exceptions, the requirements for extreme reliability and the economical use of resources in any electric system are diametrically opposed. It is not particularly difficult to design and operate a system to give any practicable degree of reliability of customer service, if no consideration need be given to the price the customer must pay. On the other hand, a system could be designed and operated with an overall economy exceeding present values, if the service standards were lowered sufficiently. The real problem is to obtain the required reliability with the maximum operating economy and the minimum of investment.

These ideas are not particularly novel, and it may seem at first thought as if there is little to present on the general subject of reliability and economy which has not already been discussed. However, in the light of the experience of the past few years, perhaps the need for an excessively high standard of reliability has been overstressed; certainly in some cases a rather high price has been paid for marginal increments above an already rather high standard. Furthermore, the industry as a whole has so actively striven for low production cost, that almost every power plant which has been built has surpassed its predecessor in this respect. Unfortunately, the improvement has usually been obtained by additional capital investment with its consequent increased annual fixed charges. It has been recognized that the total system economy is a combination of investment economy and operating cost and a balance has been struck between the two to give the lowest overall cost of power. But too frequently, the basis for striking this balance has been the expected station loading for business conditions such as obtained in the decade previous to 1930. With the advent of less prosperous times, the balance was upset and the long-time economy for the station suffered. Since it seems inevitable that the curve of general business will continue to be a series of peaks and valleys, more weight should be given that factor in balancing investment against operating cost. Perhaps, also, the time has come for a more intense study of the important factors of transmission and distribution efficiency.

Accordingly, it seems well worth while to discuss the subject in the light of the modified ideas on the relative importance of the factors involved. This paper, therefore, will outline the practises of The Detroit Edison Company affecting reliability and economy in the hope that by comparison with the facts brought out by other operating companies in companion papers, some benefit will accrue to the companies represented and to the industry as a whole. To prevent the paper from becoming unnecessarily long, only the fundamental principles and major factors in their application will be discussed, details of practise being included only where they seem particularly pertinent.

General Principles

Stated briefly, reliability of the service furnished by The Detroit Edison Company is assured; first, by the design and installation of facilities to reduce the probability of outage; and second, by a system layout and operating procedure based on segregation and sectionalization to minimize the effect of an outage. Operating economy is secured; first, by the fundamental design of each new installation for reasonably low production cost; and second, by so allocating the load between generating stations that the more economical machines carry a greater percentage of the total load in so far as the physical location of the load makes this possible.

Description of the System

The following description of the system will be clarified by an inspection of Fig. 1 which shows the geographical location and electrical connection of the principal production and transmission facilities. The Detroit Edison Company supplies electric service to a territory of 4,580 square miles in Southeastern Michigan, the extreme limits of which are mostly included within a semi-circle with the City of Detroit as the center and the eastern coastline of the state as the diameter. This area divides logically into two sections; metropolitan Detroit which includes less than 5 per cent of the total territory but 76 per cent of the people and 75 per cent of the power requirements, and the suburban area surrounding the city. The load is supplied principally by steam turbine-generators located at four power houses with an aggregate installed capacity of 825 megawatts. Two plants, Delray and Connors Creek, are located on the Detroit River within the corporate limits of the City of Detroit. The other two plants are located in suburban territory; Marysville is on the St. Clair River about 50 miles northeast of Detroit and Trenton Channel is on the Detroit River about 20 miles south of the city.

The city load is supplied at 24 kv. from five major switching stations, Waterman, Connors Creek, North-

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east, Warren and Navarre, and three distributing substations, Chandler, Cortland, and Frisbie. Waterman (the switching station for Delray) and Connors Creek are located at the river's edge but convenient to large industrial areas. Warren and Navarre are located at the western edge of the city and Northeast just outside the corporate limits at the north. Chandler is adjacent to the industrial section on the east side of Detroit, and Cortland and Frisbie are close to the geometric center of the city. A 24-kv. underground cable transmission system ties these city stations together. The Waterman Station handles the entire output of the Delray power

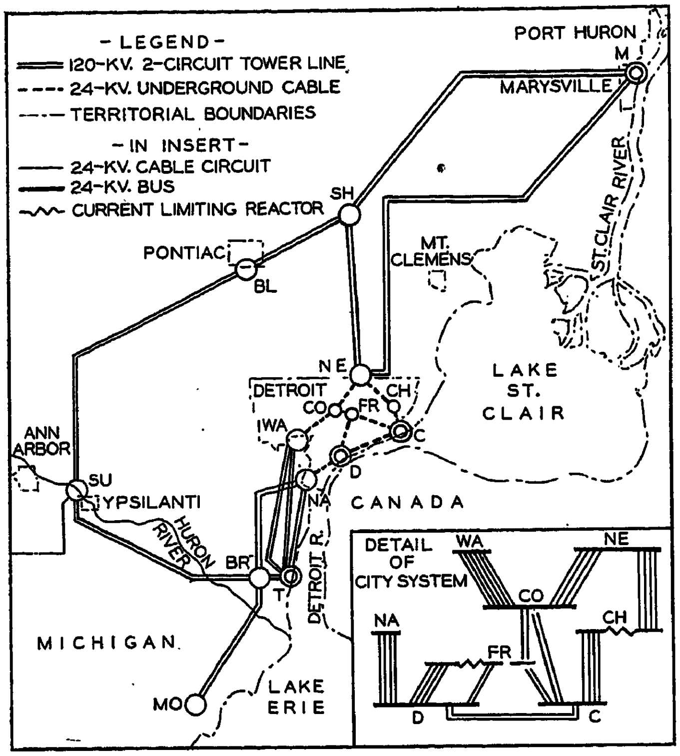

FIG. 1—THE PRODUCTION AND TRANSMISSION SYSTEM OF THE DETROIT EDISON COMPANY SHOWING GEOGRAPHICAL LOCATION OF FACILITIES

M—Marysville Power House
C—Connors Creek Power House
D—Delray Power House and Waterman Station
T—Trenton Channel Power House
BR—Brownstown Station
SU—Superior Station
BL—Bloomfield Station
SH—Shelby Station
NE—Northeast Station
WA—Warren Station
NA—Navarre Station
MO—Monroe Station
CH—Chandler Substation
CO—Cortland Substation
FR—Frisbie Substation

plant; and Connors Creek switching station the entire output of the Connors Creek plant. Northeast is supplied normally from the Marysville power house over a 120-kv. transmission system, and Warren and Navarre from Trenton Channel in the same manner. Chandler, Cortland, and Frisbie are supplied with bulk power at 24 kv. from the above major switching stations. The city load requires the entire output of Delray and Connors Creek, the bulk of the output of Trenton Channel and a goodly portion of the output of Marysville.

The suburban load is supplied by the Marysville and Trenton Channel power plants from a 24-kv. switching station at Marysville and from four 120-kv. to 24-kv. step-down transmission stations, Bloomfield, Superior, Brownstown, and Monroe, the first three of which are on a 120-kv. double-circuit transmission tower line which connects the two suburban power plants. The other station, Shelby, shown in Fig. 1 is merely a 120-kv. switching station and supplies no load.

TABLE I—DATA ON TURBINE GENERATORS

Power House	Gen. No.	Rating Mw.	Rating Mv-a.	Date in commission
Delray	6*	14	14	1909
	7*	14	14	1910
	8*	14	14	1911
	9*	15	18.75	1913
	10*	30	33.33	1919
	11	50	62.5	1929
	12	50	62.5	1929
	21	10	12.5	1931
Connors Creek	1	20	25	1917
	2	20	25	1915
	3	20	25	1915
	4	45	50	1918
	6	45	50	1920
	8*	30	37.5	1920
Marysville	1	10	12.5	1922
	2	30	33.33	1922
	3	10	12.5	1923
	4	30	37.5	1926
	5	30	37.5	1926
	6	50	62.5	1930
Trenton Channel	1	50	62.5	1925
	2	50	62.5	1924
	3	50	62.5	1924
	4	50	62.5	1926
	5	50	62.5	1927
	6	50	62.5	1929

*Emergency reserve only.

Table I lists pertinent data on the turbine generators and the one-line diagrams of Fig. 2 show the electrical connections at the power stations and at typical transmission stations.

A small amount of the load in the vicinity of Ann Arbor is furnished by hydroelectric generators located in stations along the Huron River. The aggregate installed generator capacity is only 9 megawatts.

APPLICATION OF GENERAL PRINCIPLES

Reduction in the Probability of Outage. It is the general policy of The Detroit Edison Company to be reasonably conservative in the application of facilities on the basis that an increased reliability of equipment results. In determining the capacity to be installed, the design is such that the equipment does not need to be crowded to the very limit of its output for a reasonable emergency. This is particularly true of items such as boilers, which are especially affected by overloading. For instance, at all of the plants, except Connors Creek, the boilers are conservatively rated at maximum plant output. This provides an overload capacity which,

incidentally, was occasionally very useful in that period when it was next to impossible to obtain coal with the expected heat content and, as a consequence, the boilers could not reach their maximum rating. However, advantage is taken in emergencies of the inherent short-time overload capacity of certain equipment when it is felt that such operation does not reduce its reliability. For instance, transformers and induction regulators are permitted to operate at higher than their nameplate rating for a short-time peak load period in an emergency.

In general, a voltage insulation standard higher than the minimum acceptable, has been adopted because of its important bearing on equipment failure. For instance, cable insulation is thicker than usual, the bus insulators and bushings on transformers and breakers are the next higher voltage class, and clearances to ground and between phases are greater than the minimum standards.

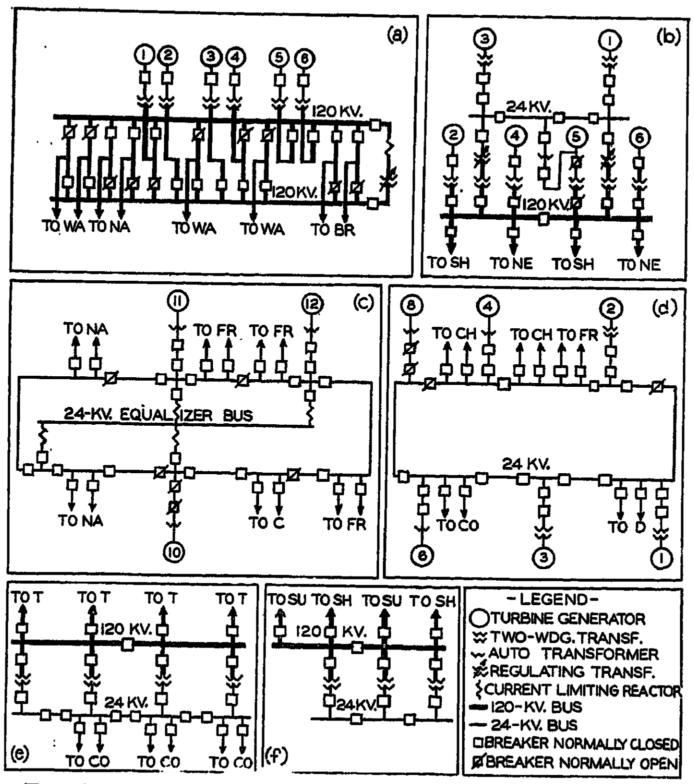

FIG. 2—ONE-LINE DIAGRAMS SHOWING ELECTRICAL CONNECTIONS AT THE POWER HOUSES AND AT TYPICAL TRANSMISSION STATIONS

(*a*) Trenton Channel Power House
(*b*) Marysville Power House
(*c*) Delray Power House and Waterman Station
(*d*) Connors Creek Power House
(*e*) Warren Station
(*f*) Bloomfield Station

It has been found that a large percentage of the trouble on electrical equipment is due to the mechanical rather than the electrical features. A study of maintenance records clearly shows any weak point in the design or manufacture of purchased items and the probable remedy can usually be suggested. By a close coordination among the maintenance, operating, and engineering departments, these defects are remedied in new equipment by designating acceptable construction for these particular features in the purchase specifications. In this way, as additional experience is accumulated, a specification is evolved which pretty well defines the acceptable mechanical construction. This often results in forcing the manufacturer to furnish somewhat special equipment, but this slight additional expense is entirely justified by the improvement in operating reliability and reduction in maintenance costs which result.

Realizing that circuit breakers are by far the most hazardous piece of electrical equipment involved in the station design, they have been eliminated wherever possible, as, for instance, in distribution stations fed at 24 kv. In these cases, cable and transformer are considered as a unit, being switched on the high-voltage side of the transformer at the sending station only, with no 24-kv. switching equipment or bus at the distribution stations. At the indoor 24-kv. switching stations, where it is impossible to eliminate breakers, a type with a minimum of oil is used on the basis that the real hazard is the large quantity of oil in the tanks. At the outdoor stations, both 24-kv. and 120-kv., oil filled breakers are used of necessity.

In power house design, two rather important features have, it is believed, materially reduced the probability of outage of production equipment. One is the use of low-voltage d-c. house service for all essential auxiliaries and its complete electrical isolation from the rest of the station. The small likelihood of trouble on the low-voltage system, and the ease with which maintenance work can be done with the bus energized, make a service interruption highly improbable; the inherently superior speed control characteristics of the d-c. motor recommend it from the ease of operation standpoint; and the economic studies indicate that for conditions as they exist on the system, based on past records, there is little cost advantage for the a-c. The second factor is the use of a unit exciting system for each machine, and the elimination of the main field rheostats. This allows the connections between exciter and machine to be as direct as possible and eliminates in this important circuit, long connections which introduce additional hazard. Furthermore, the excitation system is isolated from other circuits which, from their very extent, are more likely to give trouble.

Since no perfection of design can overcome defective installation, every effort is made to secure first class construction. A rigid inspection and test program insures that the work is properly done before the installation goes into service.

Reduction in the Effect of Outage. Since it is impossible completely to eliminate outage of major equipment no matter how much emphasis is placed on reducing its probability, the system is so designed and operated that failure will have the minimum effect on service to the customer. Throughout the system, the layout is such that the loss of any one production or transmission facility, be it boiler, turbine generator, transformer,

transmission line or bus, need not occasion loss of service to a customer. This does not mean that there are no service interruptions but most of those that occur should rightly be charged to the distribution facilities. Obviously, the different requirements as to character of service which are imposed in supplying different classes of customers affect the distribution facilities provided. Thus for residential loads, voltage regulation is stressed but a momentary interruption is not particularly objectionable, while for industrial loads, the elimination of interruption is considered vital with close voltage regulation of secondary importance. Accordingly, residential load is supplied from a distribution station with two or more separate 4,800-volt buses fed radially from 24-kv. transmission stations. In case of failure of one source, service is interrupted to one bus for a second and a half, and is restored by automatic throwover to another 4,800-volt bus which is usually fed from a different power area. On the other hand, for industrial loads, the 4,800-volt bus sections are fed radially from different 24-kv. bus sections as before, but the distribution buses are connected together through reactors and a linkage bus so that the loss of one source does not cause an interruption but may cause some voltage drop. In this case, however, the whole station is fed from one power area in order to avoid reducing the impedance between power houses by ties through distribution stations.

At each power house the running reserve in boilers and turbine-generators is maintained at all times such that if one unit is lost, the remaining units, with the relief available from the system over the tie lines, can carry the station load. The steam piping is sufficiently interconnected so that each turbine can receive steam from several boilers. The mechanical equipment, auxiliaries, coal handling equipment and the like, are designed with reserve capacity, or duplicate equipment, so that a probable failure does not impose any limitation on the major equipment, the turbines and the boilers. At each transmission station, the transformers are operated normally at such loads that in case one bank trips out, the emergency rating of the remaining banks is sufficient to carry the station peak loads.

In the electrical system, the principle of electrical sectionalization and physical segregation is employed rather freely. The degree of sectionalization can best be determined by a study of the one line diagrams in Fig. 2, which show the electrical connections at the four power plant switching stations, at a typical 120-kv. city transmission station, Warren, and at a typical 120-kv. suburban transmission station, Bloomfield. It is evident that in every case a generator or transformer can be tripped out without any interruption of service to the bus. In the case of Waterman, for instance, the load would have to be carried over a reactor until a rearrangement of buses could be made. This might cause a slight drop in voltage at the bus but that is not serious, especially since it is usually compensated for by induction regulators at the distribution stations.

In all cases it will be noted that the 24-kv. bus can be sectionalized in an emergency so that a faulted portion can be cut out by protective equipment without shutting down the complete bus. Since, as stated above, any important load is fed from two or more bus sections, the loss of one is not serious. Normally, of course, all sections are electrically connected; solidly as at Warren, through reactors and an "equalizer bus" as at Waterman, or through the substations as at the present Connors Creek station. Shortly, the new Essex station will replace the present Connors Creek switching station, and, as soon as conditions warrant, an "equalizer bus" scheme similar to that at Waterman will be installed.

At all 120-kv. stations there are two bus sections, normally tied together but arranged to separate in case of bus trouble. One circuit of each outgoing tower line is connected to each bus at the power stations so that in case one section trips out only one-half of the lines is lost. At each transmission station, except Monroe, there are two incoming double circuit tower lines. The transmission circuits are sectionalized at each station so that in case of trouble, at some point on the line, only one of the four lines into the station is out of service.

In the indoor 24-kv. stations, equipment is physically segregated where possible. Each bus section is completely enclosed in its own bus housing and in some cases additional barrier walls separate the sections. In the case of the circuit breakers, where there is the additional hazard of oil, fire and smoke, even though breakers with little oil are used, each group is completely isolated in a separate room to prevent the possibility of fire and smoke spreading to breakers on adjacent buses. At the three outdoor transmission stations, Warren, Navarre and Northeast, barrier walls are being erected between the 24-kv. buses to prevent trouble originating in one section from being communicated to the adjacent ones.

Due to the normal operation of all transmission ties in pairs, differential protection is used on both the 120-kv. lines and the 24-kv. cables, to give very fast clearing of a faulted circuit. This minimizes the disturbance to the system and eliminates any danger of instability between power houses. Recently, bus differential relaying has been installed on most of the 120-kv. and 24-kv. outdoor buses to give the advantage of rapid clearing in case of bus trouble. In the newer 24-kv. indoor switching stations, as Chandler and Frisbie, the new section of Waterman, and the new Essex Station, all electrical equipment is completely enclosed in metal housings isolated from ground except through a current transformer at one point, and equipped with fault bus relaying which again is practically instantaneous.

As a further means of localizing serious trouble, the system is operated on the power area plan. Normally each area can carry its own load without assistance from the system, the transmission ties acting mainly as

emergency reserve. In case a fault is not properly cleared by the local protective equipment and the trouble reaches serious proportions, the breakers on the transmission ties will open, as a last resort, isolating the affected section and allowing it to shift for itself, but at the same time removing the disturbance from the rest of the system.

System Planning. In planning the installation of additional facilities, the criterion for station capacity is the peak load and it must be possible to carry this load with a reasonable emergency existing. The probable total system load peaks are predicted for several years in advance from a study of past performance, the existing trend of load increase, national and local business conditions and other factors which affect load growth. The probable loads on individual substations are predicted from the same data supplemented by more detail information on the plans for industrial expansion or real estate development as affecting a particular substation. From a knowledge of the probable total system load, the probable individual substation loads, the proposed changes in load areas and the diversity factor between the peak loads of the substations in a given area, the peak load on each power house is estimated.

To determine the firm capacity of the total system, the emergency criterion which has been established is that peak load occurs when the largest machine is down for routine maintenance and the next largest trips out due to an emergency. This criterion is reasonable because of the necessity for periodic inspection and maintenance on turbine generators and is particularly so on a large system where the number of generating units makes it increasingly difficult to schedule this necessary inspection and maintenance work at light load periods. In determining the capacity of each plant, it is assumed that both the machines out of service are located at this one plant, but in this case, the relief which is available to that load area from the system over the transmission ties is added to the emergency rating of the remaining machines to determine the permissible load on the station. Obviously the firm capacity of the system is not the sum of the permissible loads at each plant as this would assume several emergencies existing simultaneously. Practically, a certain margin is maintained between the predicted peak load on the system and the firm capacity of the system in order to be able to supply an unexpected load of reasonable proportions or to handle a load growth somewhat in excess of expectations.

The emergency criterion for determining the capacity of the transmission station transformers is somewhat different because they are seldom down for routine maintenance for any length of time. In case of failure, the defective unit is replaced by the spare transformer available at each station and the bank is back in service rather quickly. Hence the permissible load on a transmission station is determined by the emergency rating of the remaining transformers with one bank down.

Provision for Reactive Kva. Provision has been made in the design of the generators to take care of reactive as well as real load. The load power factor on the high voltage side of the generator transformers may be as low as 82 per cent at times of system peak. By the time this is transferred to the generator terminals through the rather high transformer reactance and the effect of the transformer excitation is taken into account, the power factor is several per cent lower. It is quite possible that an 80 per cent power factor generator might be somewhat shy of reactive capacity in an emergency. Hence, in the later units excess reactive capacity in the generators has been obtained.

There are several small synchronous condensers and one of 30,000 kva. capacity on the system but these were installed mainly for voltage regulation. The large unit located at Northeast is available, however, to relieve Connors Creek generators of some of the wattless kva. of their load. The machines in this power plant were purchased at the time when load power factors were considerably higher than they are today and do not have the reactive kva. reserve present at the other plants.

Fundamental Design for Economy. In power plant design, a reasonable operating economy is sought, and the newer plants, of course, have considerably higher economy than the older ones. Because of the power area plan, each plant carries load which varies approximately in proportion to the system load with no station acting as a base load plant. Consequently exceptionally high economies at the expense of increased plant investment and possibly greater operating complications have not been sought, since they can be justified only by assuming base loading.

Load Allocation. To obtain the most economical operation, each load should be supplied from the power house which gives the lowest delivered cost of power including production and transmission costs. However, the ties between the power areas are limited in capacity so that the transfer of power from one area to another is correspondingly limited. With the scheme of operation adopted by The Detroit Edison Company the loads on the machines at a plant and on the tie lines into the plant must be maintained at such a point that the area load can be carried in case one machine trips out. To obtain economical loading on the machines, this requirement usually results in the transmission ties being loaded below their actual capacity. Furthermore, with the plants interconnected by the system network, it is not always possible to carry a particular load on any one power house because regulation at one plant is not entirely independent of the others and in trying to obtain the desired results at one plant, conditions at the others are adversely affected. Hence the method of allocation used is a compromise between maximum economy and practical operating conditions and is based on the station capacity weighted by the production economy and modified to take account of the physical location of the loads and the method of operation.

In applying the method, the active capacity at each plant is divided by the plant coal rate in pounds per kw-hr. Then as a first approximation, the percentage load on each plant is determined on the basis of these weighted figures. A modification is introduced to take into account the transmission loss. If this allocation does not meet the requirements of practical operation, it is further modified to take this factor into account. A specific example will explain the method more clearly. In Table II recent data for the four plants are listed.

TABLE II—METHOD OF LOAD ALLOCATION

Plant	Active generator capacity In mw.	Active generator capacity In % of total	Coal rate in lb./kw-hr.	Col. 2 / Col. 4	Load allocation in % of system load Approx.	Load allocation in % of system load Actual
Delray	110	15.3	1.12	98.2	15.3	20
Connors Creek	150	20.8	1.45	103.2	16.0	20
Marysville	160	22.2	1.07	149.7	23.3	19
Trenton Channel	300	41.7	1.03	292.1	45.4	41
Total	720			643.2	100.0	100

The active installed capacity at each plant is given in megowatts in column 2 and in per cent of the total in column 3. Column 4 shows the coal rate in pounds per kw-hr. Dividing the plant capacity in column 2 by the plant coal rate in column 4 gives column 5. Totaling these weighted figures and dividing each item by the total gives the approximate allocation of column 6. This percentage takes into account the effect of differences in production costs but does not include the effect of transmission loss. It happens that the load allotted to Connors Creek and Delray in this case is only about 75 per cent or less of the area loads of these plants. If the cost of transmitting the balance of these loads from the suburban power stations into the city load areas is considered, the city plants should carry a larger percentage of the total load. In addition, the availability of the transmission ties for emergency relief would also dictate a greater load on these stations. Without going through the detail procedure in this particular case, these factors indicated that 20 per cent each should be carried on Connors Creek and Delray. The actual load allocations are given in column 7.

The plant economy used is obtained from the records of the immediately preceding period. These figures apply only for the actual conditions which existed for that period but usually the conditions do not vary sufficiently to make correction necessary. A computation similar to the above is made periodically and the allocation changed when necessary. The same percentages are used regardless of system load because it is felt that variation with system load does not offer sufficient advantage to compensate for the operating difficulties involved.

At certain power plants there is a variation in economy among the machines. In these cases, the combination of machines which will give the highest plant economy is preferred, if this does not require some undesirable operating condition such as running a unit for an hour or two at a time.

INTERCONNECTIONS

The only central station interconnection of The Detroit Edison Company is that with the Consumers Power Company through a 30,000-kva. transformer bank and a single 140-kv. transmission line. This interconnection, of course, acts as emergency reserve and eliminates the necessity for a certain amount of running reserve in generators. Since the Consumers Power Company has a large amount of hydroelectric equipment, at times of excess water and light load on its system it can furnish dump power at an attractive cost so that a certain economy is effected at these times.

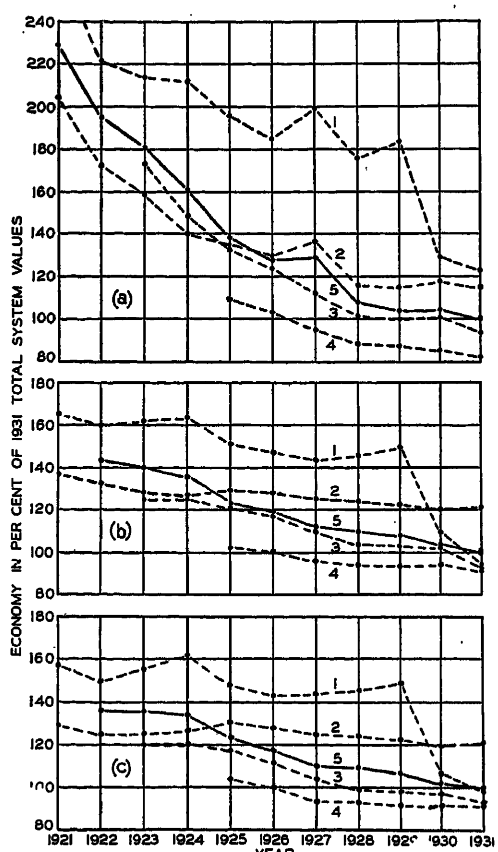

FIG. 3—YEARLY PRODUCTION DATA OF THE DETROIT EDISON COMPANY

(a) Cost in cents per net kw-hr.; 100 per cent = 0.334
(b) Coal rate in lb. per net kw-hr.; 100 per cent = 1.184
(c) Thermal efficiency in B.t.u.'s per net kw-hr.; 100 per cent = 15,780

Curve 1—Delray Power House
Curve 2—Connors Creek Power House
Curve 3—Marysville Power House
Curve 4—Trenton Channel Power House
Curve 5—Total System

In addition, there is an interconnection with the Ford Motor Company through two 30,000-kva. transformer banks. This again acts as running reserve to a certain point, but in this case the generating capacity consists of steam turbine units so there is no relatively

cheap power involved as is the case with the hydro plants.

Installation of New Facilities Ahead of Load Requirements

In general, it has not been the practise of The Detroit Edison Company to install new facilities before the load has demanded it merely to secure some added operating economy. At times obsolete generating equipment has been replaced by some of higher economy. But this was done primarily because increased generating capacity was required at that time.

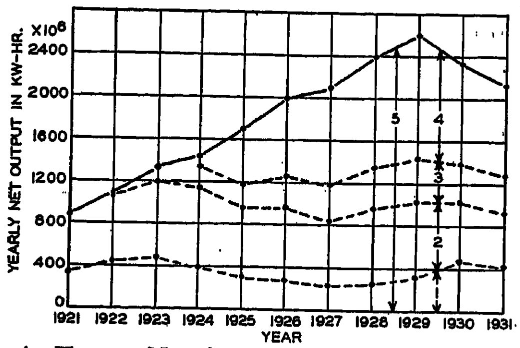

FIG. 4—YEARLY NET OUTPUT OF THE DETROIT EDISON COMPANY IN KW-HR.

1. For Delray Power House
2. For Connors Creek Power House
3. For Marysville Power House
4. For Trenton Channel Power House
5. For the total system

On the other hand, where the main reason was an improvement in reliability, there have been several instances where new substations have been built to replace old ones, or old stations rebuilt. The equipment in the old stations, principally circuit breakers, was becoming obsolete with the growth of the system, and there was some question about the ability of the stations to operate reliably under the changed system conditions. In these cases, the new or rebuilt station had more capacity than the old but the additional capacity was not always essential at the time the change was made.

Results Obtained

Due to its rather indefinite nature, there is no absolute measure of the improvement in the reliability of service which can be directly credited to the production and transmission facilities. The average number of interruptions per customer, over a period of years, or some such criterion might be used, and would indicate a marked improvement. But the measure would be a truer indication of the improvement in distribution facilities than in transmission and production facilities. However, a study of the failures of transmission and production facilities which have occurred, indicates a definite improvement and shows that at the present time such failures are of minor consequence in affecting the reliability of service to customers.

A more definite proof of the results in operating economy of production can be presented. The curves in Fig. 3 show graphically the improvement in yearly production economy for the past decade. Data are given for each of the four plants and for the system as a whole in per cent of the corresponding value for the whole system for 1931. Presented in this form, the improvement at each plant and for the system is clearly shown as well as the relative efficiencies of the different plants. Since the cost of a kw-hr. is the absolute criterion of success, Fig. 3a shows the production cost in this form. This figure includes cost of coal, miscellaneous supplies, maintenance, labor, office and executive personnel and such items. Since this value includes various factors over which the operator has little control, such as the varying price of supplies and labor, a better comparison of the actual improvement in thermal efficiency which can be credited to the method of plant operation is given by the pounds of coal per kw-hr. and the B.t.u. per kw-hr., which are shown in Figs. 3b and 3c, respectively.

Since the system output and the shape of the daily load curve have an important bearing on the cost of operation, Figs. 4 and 5 are included. Fig. 4 shows the yearly system output in kw-hr. for the last decade together with its distribution among the four power stations. Fig. 5 shows the load curves for three days in

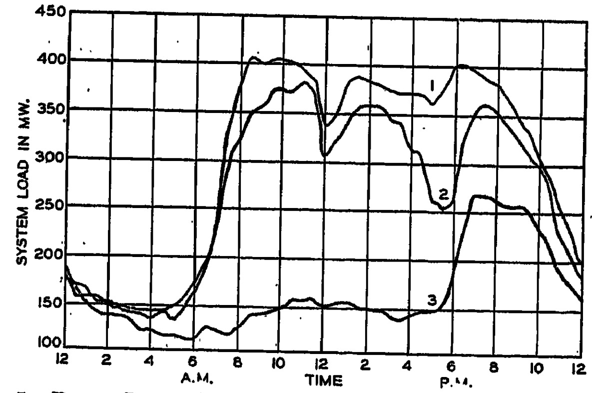

FIG. 5—DAILY LOAD CURVES OF THE DETROIT EDISON COMPANY

Curve 1—For cloudy weather week day
Curve 2—For clear weather week day
Curve 3—For Sunday

January and February of this year. One is for a cloudy week day, one for a clear week day, and the third for a Sunday.

Conclusions

In view of the results accomplished, it is felt that the fundamental principles followed have been sound. Experience has shown that in certain details of design or operation, changes can be made to advantage, and, of course, are being made as they are discovered. However, these modifications are all in the detailed method of carrying out the fundamental principles and not in the principles themselves.

Discussion

For discussion of this paper see page 888.

II—Combined Reliability and Economy in Operation of Large Electric Systems

THE EDISON ELECTRIC ILLUMINATING COMPANY OF BOSTON

BY R. E. DILLON*

Non-member

INTRODUCTION

IN the development and operation of a successfully managed public utility reliability and economy must be based on the particular conditions inherent to the locality which it serves. As a result every company's problems must have individual study, and no set and fast rules can be established for their solution. However, the policies, practises, and experiences of each, are helpful in moulding the development of others.

The business of the utility is founded upon its ability to compete successfully with the private plant in reliability and economy from the standpoints of both operation and investment.

Customers do not always require the same balance between reliability and economy and, therefore, a company may find it necessary to make some variation in its distribution practise in order to compete with a contemplated plant at the customer's location.

STATEMENT OF GENERAL PRINCIPLES

It has always been the policy of The Edison Electric Illuminating Company of Boston to give more consideration to the factors of safety and reliability of service than to obtaining the lowest possible investment and operation costs. The few exceptions to the policy are in the cases where low cost is considered by the customer to be of more importance than the risk of possible interruptions to service. However, the nearer the customer is to the center of power production, the more uniform is the balance in these respects, since there the balance is set by customers who demand the greatest reliability.

The final plan for the addition of a large block of capacity in generating or distributing facilities is the result of a compromise between those features that seek a minimum of investment outlay, to be obtained by simplicity, and those that urge complications designed to give a high degree of operating flexibility in behalf of reliability.

Here again it should be pointed out that reliability is not necessarily sacrificed in the plan for less total investment. On some occasions reliability may be assured with smaller total investment by the installation of an increased amount of spare capacity using simplified equipment and at less cost per kilowatt.

In line with this company's policy to give the most reliable service possible at the point of production, sufficient capacity is operated to allow the loss of the largest turbine in the generating stations, or the largest group of tie lines on a single tower line, or the largest tie line of a group of tie lines on separate towers, including cases where these latter are on the same right-of-way, if satisfactorily separated.

In connection with transmission, it is the policy to operate a sufficient number of transmission lines to allow the loss of the largest line to those substations which supply more than one customer, and also to those that supply one customer of sufficient importance to warrant it. However, loop service is provided to single-customer stations in cases where a spare line is not justified, when the location of two or more permits it.

Substations also are designed so that in case one transformer is lost, the load can be carried upon the remaining transformers. Here again an exception must be made for the single-customer substation where cheap power is preferable to continuity.

Continuity of service must be provided by keeping in service adequate capacity in boilers, turbines, and transmission lines; and the next concern is to allocate properly the load to such generating stations and facilities as will give the best efficiency.

Although spare capacity is installed in substations according to the policy which has been outlined, nevertheless the capacity is operated with regard for the best dollar economy.

DESCRIPTION OF THE SYSTEM

There are two main generating stations located on tide water and several small steam and hydroelectric generating stations.

The Charles Leavitt Edgar Station of 158,000-kw. capacity is located at Weymouth which is 12 miles south of Boston. The L Street Station of 210,000-kw. capacity is located one mile south from the center of Boston.

The transmission system voltages range from 110 kv. down. A large part of the system consists of underground cable at 25 kv. and 14 kv. There are two underground direct ties between the two main stations operated at 14 kv. There are underground radial feeders at 14 kv. and 25 kv. from both stations to several of the substations and some of these can be used for loose coupling.

Two of the four points of interconnection with the New England Power Association System complete a 110-kv. ring around the territory served by the com-

*Edison Elec. Illuminating Co. of Boston.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

pany. This extends from Edgar Station on the south, through Walpole, Medway, Millbury, Pratts Junction, and Tewksbury to Woburn at the north. At this point the voltage is stepped down to 14 kv. and the lines from there run underground, through several substations, to L Street Station.

Local areas are served by transformer substations along the ring.

The smaller generating stations are connected at various points to the d-c. system and to the a-c. distribution and transmission systems.

There are 116 substations, covering a territory which is spread over a radius of 30 miles from Boston. Some of these substations are customer-owned. The maps show this territory with the location of the generating stations and tie lines.

Application and Discussion of General Principles

It is possible to predict the requirements of each district of the territory with good accuracy by making a study of the system area loads over an extended period of years. In such estimates due consideration must be taken of the effect of the schedules of power rates established from time to time which are aimed to bring kilovoltampere closer to kilowatt and also to fill the valleys of the load curves.

The load density of the district served dictates the nature of the capacity which may be added, that is, by 1,500-kva. network vaults, 7,500-kva. semi-automatic substations, or larger attended substations.

The company-owned capacity requirements are affected by the interconnections. This comes as a result of planning and operating the Edison system with the New England Power Association system for the most economical mutual results without regard to separate ownership.

Cooperation extends with regard not only to the capacity requirements such as total capacity, but also to the pooling of spare capacities, to balancing of hydro capacity against steam for the purpose of conserving storage, to the spare capacity operated for protection, to the operation of the most economical units, and to the scheduling of apparatus for overhaul. The latter, due to the flexibility of rates designed to improve load factor, is today becoming a matter worthy of consideration.

The policy of always having a spare unit has been a factor in determining the size of units to install. Another factor is the relation between carrying charges on spare capacity and the decreased operating and investment charge on the larger units. Against better fuel economy and lower labor cost per kilowatt-hour in connection with larger units, there is the increased cost due to the operation of larger relaying capacity as a result of using larger units.

All of these factors are affected considerably only by the loads which are to be carried a major part of the time. These loads may be determined by a study of the load-duration curve.

On this system the last installation made has 87,500 kw. in compound capacity.

The company policy in the past has been to duplicate auxiliaries to turbines and boilers, making many connections between units, and in general, safe-guarding against all emergencies at a high cost per kilowatt of capacity installed. The policy of some companies, however, which depends upon simple installations at low cost per kilowatt of capacity and provides a greater number of spare units, is being watched very closely in

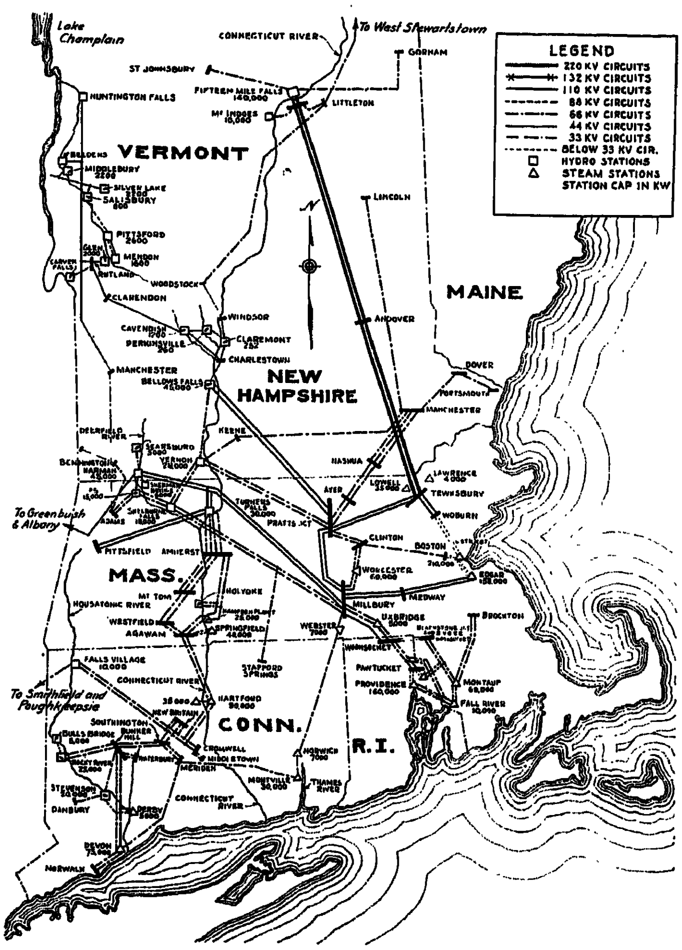

Fig. 1—Map Showing Generating Stations and Tie Lines

order to determine whether in the final analysis this policy results in lower investment charges.

Because of our policy there has never been a loss of load due to either lack or loss of generating equipment.

Proper protection of the system by spare operating capacity has served to take care of the greater part of the reactive kilovoltamperes with units rated at unity power factor. Some of the later machines have been bought, however, with excess kilovoltampere over kilowatt rating.

When the northern tie with the New England Power Association system was put into service two rotary condensers of 12,500-kva. capacity each were installed at

Woburn. This was in view of the necessity of maintaining a good power factor on the 110/220-kv. ties to Fifteen Mile Falls Station.

The proper rate restrictions have kept the power factor on the Edison system approximately 94 per cent at the time of the peak.

Ties with other systems, together with transmission ties between generating stations, have become a part of the study of additional spare capacity and have been determined by this study. This has resulted in building the present tie lines between the generating stations for 33,000-kw. capacity, which approaches the size of the largest turbine in the station having the smallest size units.

The ring-tie-transmission from the New England Power Association is of 75,000-kw. capacity from Edgar Station to Millbury and of ample capacity in the Association system to deliver 75,000 kw. at Woburn. At Woburn, however, it has not been found advisable to date to make arrangements to utilize more than about 30,000 kw.; all of which is absorbed by local areas before reaching L Street Station.

The generating station buses are operated at 14 kv. Wherever transmission has justified higher voltages the selection of type of transmission system, transformer, and connections has been determined from the economics of the case.

In some instances transformers integral with the lines have been installed. In others, transformers equipped with more flexible switching equipment for connection to buses proved desirable. Some of the latter cases arrived as the outgrowth of the former.

As has been stated substation transformers are installed for relaying. However, they are not continually kept in service and their operation may require switching. This keeps operating cost down. Capacities of substation transformers are figured according to operating-temperature limits and not according to manufacturers' ratings. This keeps investment costs down. In d-c. substations the batteries are considered as capacity for relaying purposes, although it is realized that any extended use for this purpose is very expensive. They are, however, very seldom called upon in actual practise and, therefore, this use appears justified.

The responsibility for minute-to-minute control of actual operation of relaying capacity is lodged with the system operator. For this purpose he can supplement the capacity of the company equipment by the purchase of firm or secondary power from adjoining systems.

As has been pointed out the operation of the Edison system and the Association system is carried on practically as a unit from the standpoint of economy of generation. The allocation of load among the hydro and steam stations is handled by the system operators, they having continuous knowledge of system load conditions.

After the minimum load requirements of machines needed for relayed capacity have been fulfilled, and the primary-power-takings have been utilized to their utmost value, the balance of load of the combined system is handled by generation at the most economical stations, wherever located. This may result in the transfer of load from generating stations of high operating cost on one system to stations of low operating cost on another system; such transfer being termed "interchange" power.

This plan is not essentially different from that governing the operation of an isolated company, where every effort is made for maximum output from the most efficient and minimum output from the least efficient machines. The savings realized from the power interchange, after making proper deductions for transmission line losses, are divided equitably among the companies participating in the transaction.

The interchange is based upon the immediate differences in increment costs at every period of time between production of excess power on the sending system and replacement power on the receiving system.

Under these conditions power goes from the system which is most economical to the one least economical at the time.

Accurate determination of the increment costs which are utilized in such transactions are necessary. Capital charges, except for the lines, do not enter into consideration since it is an exchange of excess power that is concerned.

However, operating costs change from season to season, from day to day, from watch to watch, and from hour to hour, and to these extents the analysis of costs must be carried in order to arrive at representative figures.

Many of the charges which actually enter into the operation during a given hour are charges which have been deferred from previous hours of production; for example, those due to banked boilers and maintenance. These deferred charges are substantial and must be included.

The no-load loss is an example of a loss which is chargeable or not, according to conditions.

Increment costs differ depending upon the turbines to which the load is added and also upon whether this is added on primary or on secondary valves.

Addition of load to a generating station may produce added repair costs due to forcing of boilers. It may also produce abnormal increases in transmission system losses due to lines being already heavily loaded. These increased costs will be in addition to the coal, water, supplies, and normal repair costs. Reduction of load on a generating station may produce unbalanced loading of high and low pressure boilers with resultant lowered economy. It may also produce non-uniform temperature gradients through turbine rotors at light loads with possible abnormal wear. In addition it may produce fuel losses through non-uniform loading of boilers. Recognition of these various factors will prevent losses due to

interchanging power on an increment cost margin which is too narrow.

In practise, the trading, and cost figuring is accomplished in the manner to be described as follows:

The load dispatchers of each system are informed of the amount of the excess power available. The tentative purchaser places a bid for a stated amount of power during stated periods. The seller quotes costs estimated from forecast conditions. The purchaser notes the spread between these costs and the estimated replacement costs on his system, and proceeds with the transaction accordingly.

After the transfer of power has been made, the transaction is figured in accordance with definite knowledge of amounts and loading conditions, and with power charges or credits through changing conditions from hour to hour. The figuring is done according to a predetermined method, so that results are always on a comparable basis. The bills are made out in accordance with these figures. Finally, checks are made of the final results with the available figures of actual production costs.

Allocation of the load between Edgar Station and L Street Station from the standpoint of economy is not a complex problem. Edgar Station is more efficient than L Street Station, largely because of the high steam pressure equipment. It is, therefore, desirable to carry the base of the load at all times at Edgar Station. However, due to a retarded growth of load in the section surrounding Edgar Station, and to limited tie-line facilities, the system is unable to absorb full capacity of the station. The remainder of the normal load is taken on the turbine primary valves at L Street Station with fuel economy equal to that of the load taken on the secondary valves at Edgar Station.

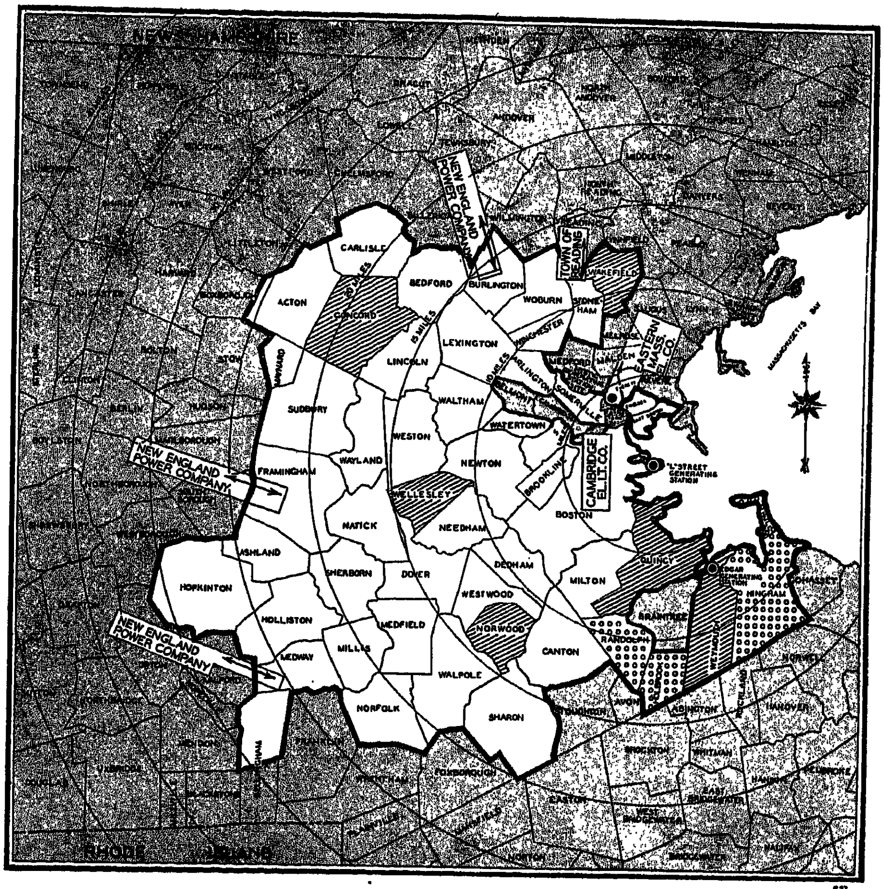

FIG. 2—MAP SHOWING TERRITORY SUPPLIED BY THE EDISON ELECTRIC ILLUMINATING COMPANY OF BOSTON IN 1931

In white areas company furnishes total requirements and distributes locally
In cross-hatched areas company furnishes total requirements in bulk
In dotted areas company furnishes total requirements through an intermediary distribution authority
Arrows indicate cooperative interconnections with other systems
● = Generating station site
⊙ = Generating station

EFFECT OF MAJOR INTERCONNECTIONS ON RELIABILITY, INVESTMENT, AND OPERATING ECONOMY

Justification of extensive interconnections between companies is sometimes difficult to establish on an

earning-power basis unless the construction of such an interconnection is part of a primary power contract, as in the case with the Association and Edison primary ties, where the cost of this primary power plus the carrying charge of the interconnection may be credited as offsetting the carrying charge for the investment in new generating facilities which would have been made necessary in lieu of the primary power purchase. On the other hand the Millbury line is a case in which the carrying charge of an inexpensively constructed transmission line has been amply covered by the savings derived purely from secondary power interchange.

The support given a system through the medium of an interconnection during abnormal loss of capacity is of incalculable value in avoiding loss of service to customers.

The reliability of interconnecting transmission lines, considering modern design and construction and also routine sleet melting programs, approaches comparison with the modern turbine unit.

A factor that is occasionally lost sight of in establishing an interconnection is the need for adequate communicating and metering facilities from the terminal points of the interconnection to the system operator. Too often the tie lines are built without ample regard for the needs of the system operator to give instant knowledge of tie-line load, frequency, voltage, and other conditions. Also the need has been established for adequate synchronizing points to permit reassembly of the system in the shortest possible time after breakapart. The investment of millions in interconnections cannot pay proper dividends in system protection without the insurance provided by carefully selected metering and communication facilities.

The subject of economy in the operation of secondary power interconnections has been discussed in connection with the necessity of obtaining cost factors. The question of economy of the primary interconnection between the Edison and Association systems has resolved itself into a comparison of costs over a reasonable term of two alternative cases; one covering the capital charges for the Fifteen Mile Falls Plant and the line to Woburn, together with the total cost of operating that plant per kilowatt-hour of output in connection with existing generating facilities; the other case covering the capital charges for an entirely new steam station of the same capacity as the primary facilities together with the total cost per kilowatt-hour of operating this plant with an output equivalent to the primary power, and giving due consideration to its value for base load service.

As would be expected, operating costs are far in favor of the Fifteen Mile Falls Plant. This permitted a wide divergence in the investment cost of the hydro and steam plants before the project became uneconomical. The limit of difference in investment was not approached and the Association was able to set a price for the power from its system, augmented by Fifteen Mile Falls, which assured success to the project and a profit to the Edison system over a period of years.

Installation of New Facilities Ahead of Load Requirements to Secure Additional System Economy and Reliability

On this system it has never been found profitable to install new facilities ahead of load requirements. None of the facilities displaced in service by this move would be displaced in book value. A scanning of the load duration curve discloses the fact that the percentage of the annual output which has to be produced by equipment installed prior to 1920 is relatively small. All equipment installed after 1920 is efficient according to present standards, and none of this can be profitably displaced.

To carry this reasoning still further, there is at best only a difference of about two mils between the operating cost of the poorest and the most efficient equipment on this system. The fixed charges per kilowatt of new capacity at the present time would be $17.00. To justify these fixed charges, therefore, would require operation at capacity for 8,000 hours per year which it is needless to say is impossible.

Changes in equipment are sometimes desirable and in specific cases they can be justified. In 1916 and again in 1921 several of the overfeed stokers at L Street Station were changed to underfeed stokers. At that time this boiler plant was in heavy service. Labor conditions were uncertain. The type of stoker and small size of the units required a large force. The nature of the work was heavy. It became difficult at times to find labor and to keep it. In the interests of reliability the change became desirable, but it also proved in consideration of advances made in stokers to be advantageous from the economic standpoint.

Another specific example is furnished in connection with the installation of a reducing valve at L Street Station. The modern extension at L Street Station is operated at 300 lb. steam pressure while the older part of the station generates at 200 lb. pressure. The older station is used now for idling capacity or standby. For this purpose, and also for the purpose of picking up relayed load, it was necessary to keep a number of the old boilers banked. In order to shut these boilers down and save banking charges and labor, it became economically advisable to install a reducing valve and desuperheater and supply the 200-lb. mains from the 300-lb. boilers where available capacity for the purpose is in service.

On our own particular system it has been found that the question of reliability is dependent upon two main factors; first, flexibility of design to permit loss of any one machine, transformer, line, or bus section without loss of customers' service; and secondly, the inherent reliability of the manufactured items such as cables, transformers, switches, machines, etc. The increasing reliability of the equipment itself has within the past few years reached a point where internal breakdown is extremely infrequent, and the adoption of routine methods of testing has permitted the location of weak spots in the insulations before these defects have had time to develop into service failures. In spite of these

conditions, proper protection requires the installation of sufficient equipment to permit the loss of any one generating or transmitting unit during the maximum load period without materially affecting the service.

The load growth in one section of a system may be so rapid that the normal extension of facilities along existing lines may be attended by an indication that voltage irregularity or loss of service may result, in which case a new investment in transmission facilities must be made to improve reliability. However, such new investment is not justified far in advance of the actual need for capacity.

Wherever the service becomes unsatisfactory additional investment which is adequate for the type of load served seems imperative.

Brief Statement of Results

Effect of Failures in Production Facilities on Customers' Services. Since the majority of large manufacturing customers are furnished with duplicate-line service, generally underground, the occasions of total interruption of service to any large single customer or group of smaller customers due to loss of transmission facilities have been negligible. Occasionally voltage fluctuations produced by system disturbances from cable faults or lightning strokes may affect the uniformity of product of some textile or paper industry, but these occurrences are fortunately few. The rare occasions on which generating units have been taken out of service on emergency have found ample reserve protection on the system to carry the load without interruption.

Percentage Reduction in Production Costs Over a Period of Years. The change from vertical to horizontal generating units with a simultaneous addition of boiler capacity at increased steam pressures and temperatures was accompanied by a decided improvement in operating economy. Later the advent of very high pressure boilers and turbines at the Edgar Station permitted a further economy increase. Furthermore, automatic substations together with modern equipment have improved efficiency and reduced labor.

Instruments have been perfected and put into service greatly helping efficient operation.

These changes came about in the course of providing for the growth of load. They were attended also with increasing education on the part of the attendants towards efficiency and an increasing vigilance of all forces against losses.

All these contributing elements together with the policies which have been outlined here have resulted in a reduction in production cost. A comparison of total operating cost per kilowatt-hour covering generating stations, substations, and purchased power for the years 1920 and 1930 shows that a reduction of 62.3 per cent took place.

Whenever changes of particular equipment were advised a large gain had to be assured in order to win approval for the change and in all cases approved the figures left no question to be raised.

Most careful consideration has always been given to the problem of replacing capacity solely for better operating economy. Many replacements have been made in past years, but at the present time none can be justified because fixed charges which would be incurred on new equipment prove equal to a very large percentage of the total cost of operating the old equipment.

Discussion

For discussion of this paper see page 888.

III—Combined Reliability and Economy in Operation of Large Electric Systems

PHILADELPHIA ELECTRIC COMPANY SYSTEM

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and
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Synopsis.—This paper discusses the practises in use on the Philadelphia Electric Company system in attaining the maximum system economy consistent with high degree of service reliability. The system comprises not only steam electric stations of different efficiencies, but also a large hydroelectric plant and a major high-voltage interconnection with two large neighboring utilities, so that problems of operating economy are both highly important and complex in character.

The paper also directs attention to problems of investment economy with a view toward securing the best balance of fixed charges, operating costs, and service reliability.

* * * * *

INTRODUCTION

MAXIMUM system economy is attained when the sum of operating costs plus fixed charges on investment is a minimum. Considerations of reliability usually lead to increased capital investment for sturdier facilities and for spare equipment, and consequently add to the fixed charge burden. Fortunately, however, operating costs are to some extent inversely proportional to fixed charges, and analyses of system performance will often reveal operating savings which can result from judicious use of investment in spare facilities. Indeed, it is frequently the case that new fixed charges can be deliberately incurred because they will be more than offset by the operating savings accruing from the new investment. However, it is also frequently the case that new investment must be made solely to improve service dependability.

It is the purpose of this paper to discuss practises followed on the Philadelphia Electric Company system from the standpoint of production facilities in attaining highest system economy consistent with high degree of service reliability. Production facilities include generating plants, 220-kv., 66-kv., and 13-kv. transmission tie lines, and transmission substations. For convenience, this combination will be referred to as the "equivalent generation system."

Statement of General Principles

In the development of the Philadelphia Electric Company system, certain general principles have been followed in the installation and operation of reserve facilities on the equivalent generation system. These general principles are briefly enumerated below and will be discussed more fully in a later section of this paper.

FROM THE STANDPOINT OF RELIABILITY

Generating Capacity. Reserve generating capacity shall be equal at least to the capacity of the largest generating unit. A major portion of the reserve should be located within the system with the remainder readily available from adjacent interconnected companies without imposing an undue burden on transmission facilities.

220-Kv. and 66-Kv. Transmission. Sufficient 220-kv. and/or 66-kv. transmission capacity shall be provided between major generation and transmission centers so as to insure that reserve generating capacity available at any point on the system can be made available as necessary at any other generating location and also to insure that upon failure of any one transmission line, the remaining capacity is sufficient to carry the system load.

Transmission Substation Transformer Capacity. Sufficient transformer capacity shall be provided so that failure of any transformer bank may occur without impairing the ability of the system to carry the load existing at the time of failure.

FROM THE STANDPOINT OF OPERATING ECONOMY

Allocation of Hydroelectric Energy. Run-of-river hydroelectric energy shall be allocated so as to reduce steam station costs to a minimum.

Allocation of Boiler Capacity for Reserve. Boiler capacity required for reserve shall be allocated in the most economical manner after having provided for local reserve requirements in accordance with the principle that sufficient boiler capacity shall be provided and so operated that failure of any piece of equipment at any time will not impair the ability of the system to carry the load existing at the time of failure.

Allocation of Steam Turbine Capacity for Reserve. Steam turbine capacity required for hot reserve shall be allocated in the most economical manner in accordance with the principle that the failure of any piece of equipment, at any time, will not impair service.

Allocation of Steam Station Load. Steam station load shall be allocated to individual steam generating stations in the most economical manner within minor transmission limitations so as to obtain minimum steam system cost per kilowatt-hour delivered from the transmission system.

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Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

Transmission Tie-Line Losses. Transmission tie-line losses shall be considered in arriving at correct load allocations.

Description of the Philadelphia System

The Philadelphia Electric System has developed as a closely-knit system of the so-called solidly linked type, although for a number of years, 66-kv. lines have been paralleled at some substations only through low-voltage buses, and lately under certain conditions, the system has been even further sectionalized. The system as a whole now consists of seven major generating stations aggregating more than 900,000 kw. in generating capacity, ten 220-kv. and/or 66-kv. transmission substations, nearly 60 frequency changer, railway and distribution substations, and 315 circuit miles of 220-kv. and 66-kv. transmission, 1,500 circuit miles of 33-kv. and 13-kv. transmission, and 3,900 circuit miles of distribution circuits. In addition a major interconnection at 220 kv. has been established with the Pennsylvania Power and Light Company and the Public Service Electric and Gas Company of New Jersey. Two other connections have been made with the Public Service Company, one at 66 kv. and one at 26 kv. Fig. 1 shows the general plan of the system; major switching details are shown in Fig. 4 of another paper.[1]

All of the generating stations are connected directly or indirectly to the 66-kv. transmission system through transmission substations, and the 66-kv. transmission lines are essentially the backbone of the system.

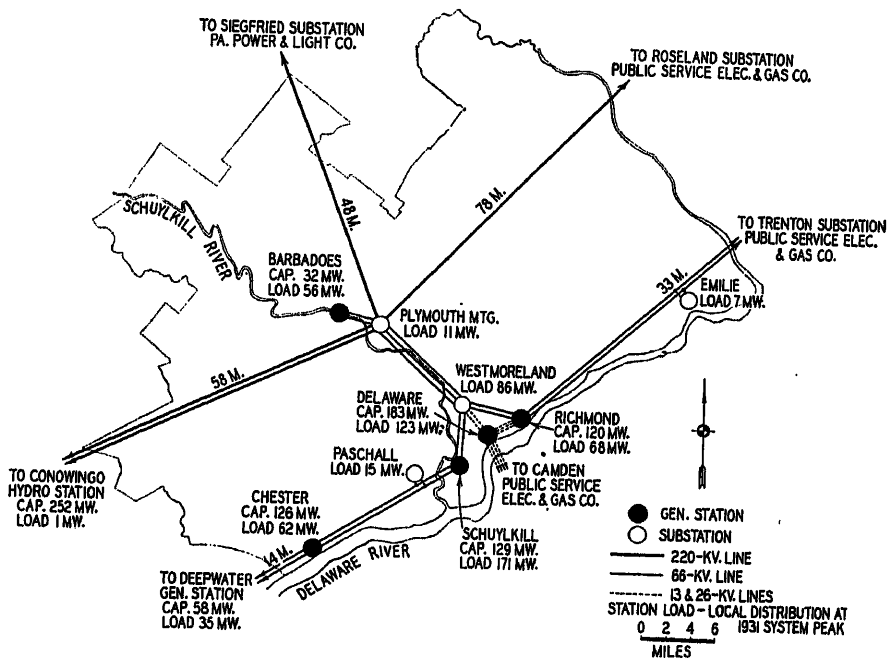


FIG. 1—PHILADELPHIA ELECTRIC COMPANY MAIN TRANSMISSION SYSTEM—1931

1. For references see Bibliography.

Application and Discussion of General Principles

From the Standpoint of Reliability

Generating Capacity. Reserve generating capacity is a serious burden on investment economy, although in many cases the additional fixed charges so incurred can be largely offset through normal operation of spare capacity to secure maximum operating economy. Nevertheless it is frequently necessary to maintain a considerable amount of capacity in older and less efficient stations mainly for reserve capacity in event of failure of the more economical normally operated equipment during the annual system peak load period. From this standpoint, it would be desirable to install new generating units in small capacities.

However, investment economy is enhanced by installing the largest possible size of unit consistent with future load growth so as to secure minimum investment cost per kilowatt of generating capacity. In this connection, accurate forecasts of future loads are essential, for on present day interconnected systems an error of only 2 or 3 per cent may mean an excess or deficiency of 30,000 kw. to 50,000 kw. in generating capacity. Economies to be secured over a period of years by maximum utilization of existing and available sites through the adoption of the largest units justified by future growth may more than offset the disadvantage of maintaining the larger amount of generator reserve. The size of machine which is to be installed can be determined on an economic basis only by a balance of these factors.

With machines of given ratings installed on a system, it becomes a matter of careful judgment based on experience to determine the number of simultaneous machine outages for which reserve must be provided. On the Philadelphia Electric Company system, it has been found satisfactory to provide for the single loss of the largest unit. Only on three occasions since 1919 have difficulties arisen with generator units during the peak season, and in each case only one unit was involved. In one case, the unit was returned to service in about twelve hours, and in the other two cases, the units were able to resume service at reduced capacity pending complete repairs.

It should be noted that reserve capacity on the Philadelphia system at the present time is considerably greater than the largest unit. This is accounted for by the fact that system load growth has not yet overtaken the large installation necessary at Conowingo for the economical development of the Susquehanna River, and by the effect of the present business depression.

There are four important reasons why it is satisfactory in Philadelphia to provide generator reserve over the system peak for the loss of only the largest generator.

The first reason is that generating equipment has attained a high degree of reliability as a result of constant improvement in design and construction.

Secondly, maintenance schedules provide for thorough inspection and overhauling of each generator periodically, thereby reducing the likelihood of failure. These schedules are based on a minimum of 6,000 service hours and a maximum of two years, between inspections.

The third reason lies in the fact that, as the system has grown, the rating of generators installed has increased progressively until now spare capacity provided against the outage of the largest unit over the peak also provides for the outage of two or more of the medium or small size units, should such double outages occur. The generating plant of the Philadelphia Electric Company includes 25 generating units with individual ratings ranging from 20,000 kw. to 60,000 kw. The few units with ratings under 20,000 kw. are seldom operated and because of their relative unimportance, need not be considered here. There are only three units in the 60,000-kw. class—two at Richmond and one 58,000-kw. unit at Deepwater. These three units, although comprising 20 per cent of the total capacity, represent only 12 per cent of the total number of generators rated at or above 20,000 kw. However, 19 generators or 76 per cent of the total number, comprising 72 per cent of the total capacity, are rated from 30,000 to 36,000 kw. It is apparent, therefore, that should a double outage occur, the probability is that it would occur in the medium or small-unit class and, practically, reserve therefor is provided if reserve is maintained for single outage of the largest unit.

The fourth and probably the most important reason is found in the characteristics of the system load. As in other metropolitan areas, the annual peak load occurs about 5 p.m., generally on a December day, and is extremely sharp. The season of these extreme peaks is only from two to three months' duration. During the remainder of the year, a portion of the generating capacity must be idle. Moreover, even during the peak season, the variation in daily peaks is such that except on relatively few days, reserve capacity is available for greater outages than loss of the largest unit. Analysis of several peak seasons has shown that on more than 90 per cent of the days in the peak season (November, December, and January), the outage of an additional 30,000-kw. unit is provided for, and on more than 60 per cent of the days, the outage of an additional 60,000-kw. unit or two additional 30,000-kw. units is provided for.

In general, the shape of the daily load curve and seasonal variations in the daily peaks have an influence on justified generator reserve capacity particularly since, where high loads persist, there is less opportunity for proper maintenance.

220-Kv. and 66-Kv. Transmission. From the standpoint of investment economy, it is necessary, of course, to secure that number and arrangement of transmission lines which will satisfactorily take care of the present and expected future loads under those emergency conditions which occur with reasonable frequency.

As will be seen from Fig. 1, the high-voltage transmission system in the Philadelphia territory is at the present time essentially a twin-circuit system. Between Plymouth Meeting and Westmoreland Substations, however, three circuits on two tower lines have been installed, primarily to increase the reliability of this very important transmission link.

The 220-kv. Conowingo-Plymouth Meeting System is so designed that each circuit is capable of transmitting the present maximum output of the Conowingo plant. Although initial experience indicated that these lines are subject to more severe lightning hazards than was anticipated, it appears that by the recent application of high-speed oil circuit breakers and relays, the requirements of the design have been met with minimum hazard from instability. The remainder of the 220-kv. system, comprising the 220-kv. interconnection, is essentially a duplicate line system although only one line is provided between each two of the three companies. With this triangular arrangement, any one leg of the triangle may fail without severing the connection of the three parties.

On the 66-kv. transmission system, experience has indicated that outage of only one circuit need be anticipated. Of the total number of circuit miles comprising this system, about 74 per cent is double-circuit aerial construction with two ground wires, 6 per cent is single-circuit aerial construction with one ground wire (on double-circuit towers), and the remaining 20 per cent is double-circuit underground construction, that is, six single-conductor cables in one bank of ducts. On lines within the equivalent generation system, double-circuit

failures resulting from lightning storms or from other causes such as accidental contact with foreign bodies, occur but rarely. Single-circuit failures are expected and do occur occasionally, particularly on the underground portion of the system, but it is the general experience that transmission failures on the high-voltage system do not result in interruptions to customers' service—and this would seem to be the criterion in judging the success or failure of the transmission system.

Since single-circuit outage only need be anticipated, the locations of generating plants and the arrangement and capacity of the high-voltage transmission system are such that any line may fail without impairing the ability of the system to carry the load existing at the time of failure.

It is to be noted that the capacity of the high-voltage transmission system is not necessarily determined by system peak loads. With the most economical generating plants located at a distance from some of the load centers, as they are in the Philadelphia system, it may be desirable to carry the heaviest loads on parts of the transmission system at off-peak periods, and consequently, examination of such periods may expose conditions which make it economical to increase the capacity of the transmission system.

Transmission Substation Transformer Capacity. Sufficient transformer capacity is provided at transmission substations for the supply of other transmission lines or large local loads so that failure at any time of the most heavily loaded transformer bank in any substation will not impair the ability of the system or the substation to carry the load existing at the time of the failure. In some cases transformer outage may require reallocation of load among generating plants. In other cases, the load on the faulty bank may be transferred to remaining banks or to other sources.

In this connection, it seems apparent that the use of forced air transformer cooling and the operation of transformers on a temperature basis can effect large savings in reducing the amount of spare transformer capacity which it is necessary to provide.

From the Standpoint of Operating Economy

Allocation of Hydroelectric Energy. The Conowingo Hydro Station with a generating capacity of 252,000 kw. generates in a normal hydro year approximately 40 per cent of the total energy supplied by Philadelphia Electric Company. Conowingo is a run-of-river plant, and, therefore, the energy output is dependent on the flow of the Susquehanna River. The approximate flow is forecast the latter part of each week for the following week in order to determine the steam station boiler schedule for that week. Each day an accurate estimate is made of the daily kilowatt-hour output from Conowingo for the following day by the hydrologer at Conowingo, who bases his estimate on the flow of the main branch and tributaries of the Susquehanna at various locations on the watershed, and a general knowledge of the actual and expected rainfall on the drainage area.

The most economical allocation of available hydro energy is obtained, first, by utilizing all the energy available from the river within the limits of plant capacity, and second, by utilizing this energy to obtain the maximum hydro capacity and thereby reduce steam station peak and energy costs to a minimum. This is accomplished by allocating a block of the system daily load curve, Fig. 2, of such proportions that the area of the block corresponds to the available energy to be generated from the total flow of water for the particular day and the ordinate of the block corresponds to the maximum hydro capacity.

Referring to Fig. 2, the higher the position of the Conowingo block on the load curve, the less will be the area of this block, which is proportional to the Conowingo energy output. The steam base load, indicated in Fig. 2, may be defined as that load above which Conowingo operates and takes all load variations up to the limit of its capacity. When the system load exceeds the steam base load plus the full capacity of Conowingo, the excess must be carried as steam peak, the steam then taking all variations in system load.

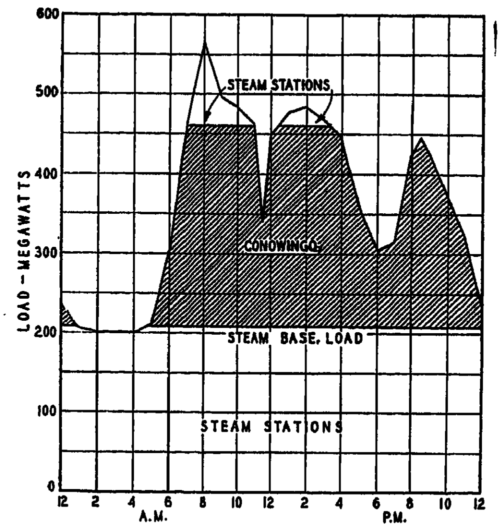


Fig. 2—Daily System Load Curve Showing Load Allocated to Conowingo

There is a definite relation between the steam base load and the Conowingo daily energy output for a given daily system load. This relation is utilized in determining the steam base load for each day by using the curves in Fig. 3, based on an available hydro capacity of 252,000 kw. The load dispatcher determines from these curves the steam base load corresponding to a given Conowingo energy output and the daily system energy generation which he estimates for the following day. The variations of the actual daily Conowingo and system outputs from the estimate are absorbed by allowing the amount of water stored in the Conowingo pond to vary. The curves in Fig. 3 are within the accuracy of

predictions of river flow and system output, regardless of the seasonal variation in the shape of the daily load curve.

Allocation of Boiler Capacity. The scheduling of boiler capacity for each steam station is done on a weekly basis in order to reduce boiler starting losses to a minimum. The number of boilers required for the week is determined from the estimate of weekly system peak load and the average steam base load for the week, which is based on the Conowingo estimated output for the week. If the difference between the system peak

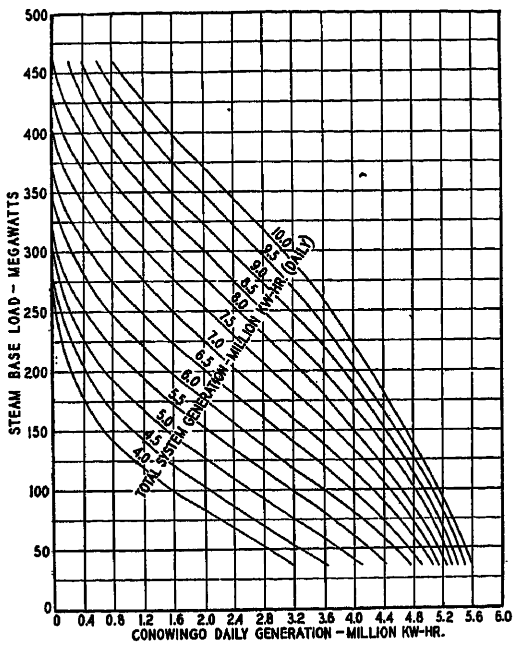


FIG. 3—CONOWINGO LOADING CHART

7 machines available at Conowingo
Capacity = 252,000 kw.
Available total peak capacity without additional steam capacity = 252,000 + steam base. If steam peak is greater than this available peak the steam peak capacity must be increased to make up the difference

and the steam base load is less than the available Conowingo capacity, the steam peak is then the steam base load, inasmuch as the excess of the system load above the steam base load can be carried entirely on Conowingo. This is the case during periods of low river flow. When the difference between the system peak load and the steam base load is greater than the available Conowingo capacity, the full hydro capacity can be utilized and the steam peak load is then the difference between the system peak load and the Conowingo capacity.

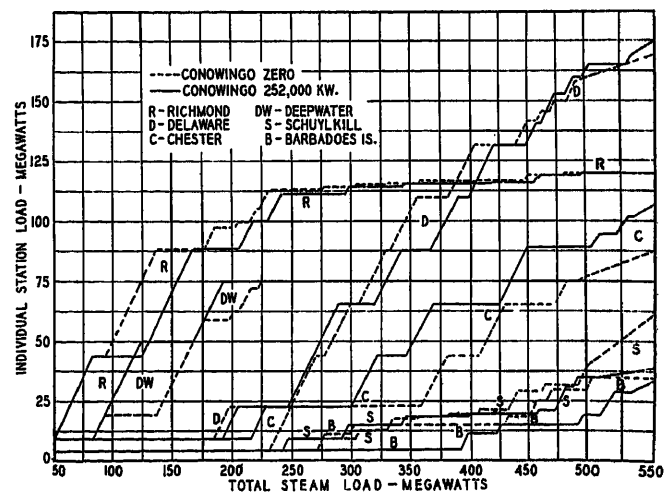
The total number of boilers required for system reserve is based on the steam peak load and the reserve required for the failure of any piece of equipment on the system.

The boilers are allocated to the individual generating stations as far as possible in the most economical manner, although it is generally necessary to operate some boiler capacity at less efficient stations in order to protect that portion of the system against the failure of any piece of equipment supplying it.

At times with a high steam station load factor, it becomes economical to operate additional boilers in excess of reserve requirements. The additional boilers reduce the average rating on each boiler with consequent improved efficiency during the heavy load periods which more than offsets the additional banking losses.

Allocation of Steam Turbine Capacity. Sufficient turbine capacity must be scheduled in the different parts of the system at all times so that the failure of any piece of equipment will not impair service. In economically scheduling turbine capacity in accordance with reliability requirements, the no-load costs as well as incremental costs on the turbines in each station are considered. A reduction in incremental costs can sometimes be effected by placing an additional turbine in service in excess of reserve requirements. This condition occurs when the turbines are being operated with the overload valves partly open, where their incremental costs are higher. The saving in incremental costs must be greater than the no-load costs on the turbine to justify placing it in service.

Allocation of Steam Station Load. The load dispatcher determines the most economical allocation of steam load and turbine capacity among the individual steam generating stations by means of a steam load allocation chart, Fig. 4. The objective in working out a steam load



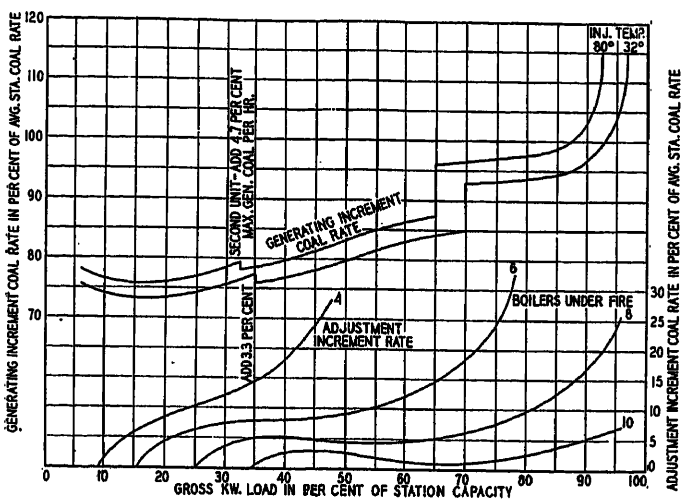
From *Electrical World*, Oct. 11, 1930.

FIG. 4—STEAM LOAD ALLOCATION CHART

allocation chart is to obtain minimum system cost per kilowatt-hour delivered from the transmission system. This can be obtained in practise by considering fuel costs only, as the cost of fuel is by far the largest item of incremental cost and any other items of cost other than fuel tend to cancel each other on an incremental basis.

Any correct load allocation must be made on an incremental basis, and is arrived at by allocating each increase in load to the station having the lowest incre-

mental fuel rate corrected for transmission losses. The incremental coal rate may be defined as the pounds of coal required to produce an increment of one kilowatt-hour in the net station output at a given station load. The accuracy of a steam load allocation chart depends, in large measure, on the accuracy of the steam station performance data used in developing the steam load allocations.



From *Electrical World*, Oct. 11, 1930.

FIG. 5—INCREMENT COAL RATE CURVES

The incremental coal rate curves, Fig. 5, for each station provide the basic information not only for correct load allocation but also for the accurate cost data necessary in interchanging power economically between interconnected systems. In Fig. 5 the incremental coal rates expressed in per cent of average station coal rate are shown in relation to station loading. Adjustments below the main curves are for the particular number of boilers which are under fire in the station and are added to the values given by the main curves to obtain the total incremental coal rate.

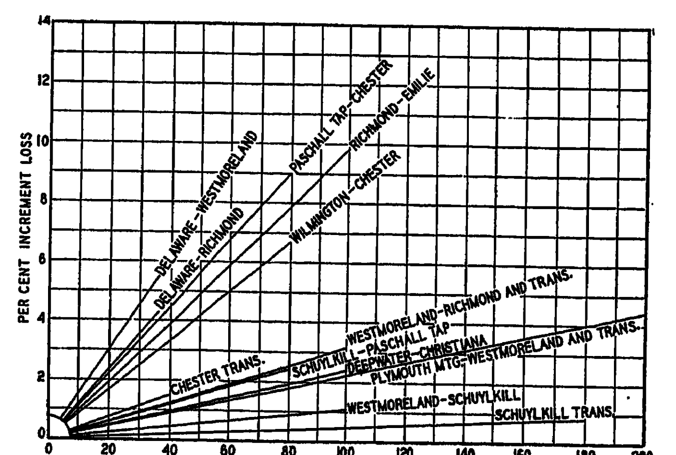
Transmission Tie-Line Losses. Economic loading of generating stations usually results in the transmission of considerable power over tie lines. Obviously, the transmission tie-line loss involved must be considered in determining correct load allocations. To facilitate the determination of the additional losses incurred in transmitting an additional block of power over tie lines from a generating source to a distributing point, transmission line increment loss curves, Fig. 6, have been developed. The per cent increment loss at a given transmission line load may be defined as the ratio of the incremental increase in loss to the incremental increase in load. If a transmission line is carrying a given load, A, and an additional block of load, B, is superimposed on the existing load A, the additional loss in per cent of load B resulting from load B is obtained directly from the incremental loss curve by entering the curve at a loading midway between the initial and final loading. If a given block of load is transmitted from a generating source to a distributing point over a number of transmission lines, all operating at different loadings, the net increase or decrease in loss resulting from transmitting the block can be readily determined by algebraically summating the percentage incremental losses on all the transmission lines. A net decrease in loss may result instead of a net increase, as it is entirely possible that by transmitting the block of load some of the transmission lines will be reduced in loading. The per cent incremental loss curves are useful not only in determining load allocations, but also in correcting costs of interchange power between interconnected companies for transmission losses.

The 220-Kv. Pennsylvania-New Jersey Interconnection

The Philadelphia Electric Company interconnection with the Pennsylvania Power and Light and Public Service Electric and Gas Companies at Plymouth Meeting has resulted in greater reliability to all the systems. The reliability results from the diversity of occurrence of failures on the individual systems. In other words, experience has shown that when a failure occurs on one system even to the extent of complete failure of a generating station, the other interconnected companies can render emergency assistance by supplying from their reserves the necessary load to maintain complete continuity of service.

Savings from the interconnection result from diversity in various forms as follows:

1. Diversity of the loads of the individual companies resulting in reduced combined peak load and consequent reduction in necessary plant capacity investment and in operating peak costs.



From *Electrical World*, Oct. 24, 1931.

FIG. 6—TRANSMISSION LINE INCREMENT LOSS

2. Diversity of occurrence of failures resulting in lower combined reserve requirements and consequent reduction in necessary plant capacity and operating reserve costs.

3. Diversity of installation of new plant capacity resulting in staggered construction and economical utilization of available sites.

4. Diversity in utilization of economical plant capacity resulting in the economical interchange of energy.

Installation of New Facilities for Economy and Reliability

New facilities have been installed from time to time prior to load growth requirements in order to secure additional system economy or reliability or both. Each installation has been carefully studied, and either the estimated operating savings have shown ample margin over the additional fixed charges incurred through advancing the time of installation, or a commensurate gain in reliability has been realized. Specific examples of facilities which have been installed to secure additional system economy and/or reliability are (1) a 66/33-kv. transformer bank at Plymouth Meeting and (2) the third 66-kv. transmission circuit between Plymouth Meeting and Westmoreland Substations. The transformer installation permits shut-down of the Barbadoes Island Generating Plant during the greater portion of each year, thereby effecting operating economies in excess of the additional fixed charges. The transmission line, although effecting some operating savings (which, however, are not sufficient to offset the new fixed charges), was built primarily to increase system reliability, and operating experience during the summer following its installation fully justified this decision.

Results

The reliability of production facilities of the Philadelphia Electric System is indicated by an analysis of the factors affecting customers' service. In 1931, no interruptions to customers' service were caused by the failure of production facilities and experience in other years has been generally satisfactory.

The operating economies obtained have resulted in a steady reduction in fuel rate per kilowatt-hour. The following tabulation shows the pounds of coal burned per kilowatt-hour expressed in per cent of the 1926 values:

Year	Steam system fuel rate lb. coal per kw-hr. per cent of 1926 value
1926	100 per cent
1927	97 per cent
1928	99 per cent
1929	93 per cent
1930	89 per cent
1931	84 per cent

The only new and more efficient generating capacity added during the entire period was Deepwater Station, the Philadelphia Electric Company's share of which amounts only to 8.4 per cent of the total system steam capacity. The increase in fuel rate per net kilowatt-hour in 1928 was caused by the initial operation of the Conowingo Hydro-Electric Station, which necessitated running steam stations at greatly reduced load factors with abnormally large hot reserve to maintain reliability during the period of preliminary operation.

The effect of economical load and reserve allocation is indicated by the following tabulation showing the B.t.u. per net kilowatt-hour for various steam stations expressed in per cent of the steam station B.t.u. rate for the year 1931. The station capacity in per cent of the total system steam capacity and the energy generated by the various stations in per cent of total steam generation for the year 1931 are also shown.

Stations	B.t.u. per net kw-hr. year 1931 per cent of steam system B.t.u. rate	Station capacity per cent of total steam capacity	Energy generated year 1931 per cent of total steam generation
Deepwater	78 per cent	8.4 per cent	24.8 per cent
Richmond	88 per cent	17.4 per cent	36.4 per cent
Delaware	115 per cent	26.6 per cent	22.0 per cent
Chester	120 per cent	18.3 per cent	12.1 per cent
All other steam stations	183 per cent	29.3 per cent	4.7 per cent
Steam system	100 per cent	100 per cent	100 per cent

The B.t.u. rates for only two stations, Deepwater and Richmond, were better than that for the system in spite of the fact that the combined capacity of these two stations is only 25.8 per cent of the total steam capacity.

These results have not been obtained at the expense of abnormally high carrying charges. All facilities installed to increase operating economy have been required to show operating savings in excess of fixed charges.

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Discussion

For discussion of this paper see page 888.

IV—Combined Reliability and Economy in Operation of Large Electric Systems

CHICAGO DISTRICT

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and

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Synopsis.—The paper outlines the load characteristics, generating stations, and transmission lines of the Chicago territory and particularly the power supply of Chicago proper.

The economics of the scheme of supply are discussed from the points of view of interchange energy agreements, comparative increment fuel costs of generating stations, increment losses of transmission lines, load schedules, remote metering and load dispatching, economics of 550- to 650-lb. units, automatic frequency regulation, control of wattless mva. voltage and phase angle.

The reliability of the system is outlined with respect to the design of generators, switchgear, transmission lines and cables, relay protection, methods of operating, and reserve capacity.

From the experience gained in the Chicago territory conclusions are drawn as to the policies of economy and reliability which have been adopted in operating the system.

* * * * *

INTRODUCTION

In 1928 in a paper before the A.I.E.E., Mr. H. B. Gear[1] outlined the main features of power generation and interconnection for the Chicago District and the surrounding territory of the Middle West, and in January, 1930, Messrs. G. M. Armbrust and T. G. LeClair[2] outlined the main design features of the 25-cycle and 60-cycle systems of the Chicago District.

This paper deals essentially with the power generation features added since that date, and the improvement in economies that have been obtained by the methods followed in the Chicago District in the generation and transmission of power.

DESCRIPTION OF CHICAGO TERRITORY

Fig. 1 is a map of the territory embracing an area of approximately 20,000 square miles. The operating companies that supply this load which amounts to about 5,758 million kw-hr. per year are the following:

Commonwealth Edison Company with about 1 per cent of the area and about 73 per cent of the load serves Chicago proper, as shown in area *A* and in more detail in Fig. 2.

The Public Service Company of Northern Illinois, the Northern Indiana Public Service Company, and the Western United Gas & Electric Company serve the remainder of the territory embraced by *B*. The area of about 8,000 square miles supplied by these four companies is ordinarily called the Chicago District, and these companies work together by means of an Interchange Energy Agreement to facilitate minimum fixed charges and maximum economy in the operation of their interconnected system.

The remainder of the territory is supplied chiefly by the Illinois Northern Utilities Company, the Central Illinois Public Service Company, the Illinois Power & Light Corporation, the Central Illinois Light Company, and the Central Illinois Electric & Gas Company.

The power is supplied by the main generating stations of the various companies located as shown in Figs. 1 and 2. These naturally fall into two groups—the six closely linked stations around the Chicago area with a total of 1,480 mw. and the more loosely linked distant stations with a total of 538 mw. Practically all of these stations are interconnected by 66-kv. and 132-kv. underground and overhead ties of 60 mva. each and larger.

There are 132-kv. major connections to outside companies shown in Fig. 1 from Michigan City to the American Gas & Electric Company's system extending eastward, from Waukegan north to the system of The Milwaukee Electric Railway & Light Company centering at Milwaukee, and from Belvidere north to Janesville and Sheboygan, Wisconsin.

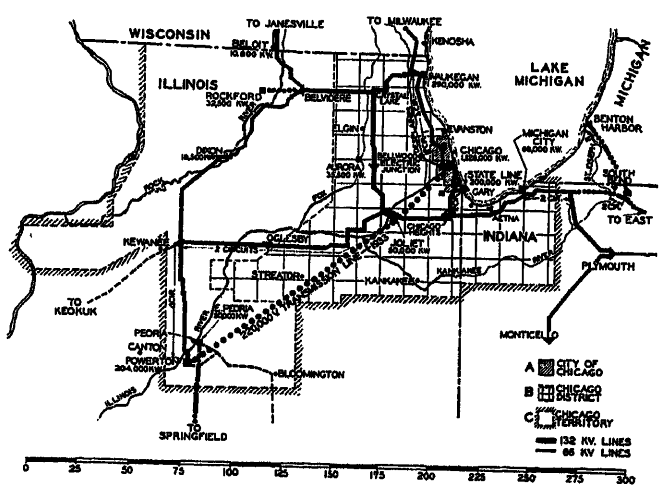

FIG. 1—MAP OF CHICAGO TERRITORY

GROWTH OF LOAD IN CHICAGO

Fig. 3 shows the load growth since 1910 and indicates particularly the change in 25-cycle generation. The distribution system at 25 and 60 cycles has been described by others.[2]

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†Asst. Electrical Engr., Sargent & Lundy, Inc., Chicago, Ill.

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Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

Outside Supply to Chicago

The importance of the interconnections in supplying power to Chicago is apparent from Table I, which indicates that in 1931, 41.3 per cent of the power consumed in Chicago was brought into the city from outside. The economics of this arrangement and the reliability of the supply from outside the city are therefore of the greatest importance.

TABLE I—DISTRIBUTION OF POWER GENERATED, PURCHASED, AND SOLD IN CHICAGO
(In Millions of Kw-Hr.)

Year	1928	1929	1930	1931
Item 1. Kw-hr. used in Chicago	3,851	4,276	4,191	4,024
Item 2. Kw-hr. generated by Commonwealth Edison stations for use in Chicago	3,542	3,466	2,855	2,364
Item 3. Kw-hr. purchased from Waukegan	276	232	236	289
Item 4. Kw-hr. purchased from State Line		418	812	952
Item 5. Kw-hr. purchased from Powerton	33	145	285	419
Item 6. Total purchased	309	810	1,336	1,660
Item 7. Purchased in per cent of kw-hr. used	8.0	18.9	31.8	41.3

Item 2 gives the amounts generated in the Chicago stations for use of customers in the city of Chicago. These stations generate some additional power that is used outside Chicago.

Item 6 gives the amounts brought into Chicago from the stations outside the city for use of customers in Chicago.

Item 7 gives the percentages of the kw-hr. brought into Chicago to the total amount used in Chicago.

Economical Operation of the Chicago District System—Interchange Energy Agreement

It is apparent that the interests of the various companies serving the Chicago region are so closely interlinked that a cooperative policy must be adopted in connection with the supply of power and extensions to the system.

For this purpose a Power Supply Committee consisting of executives of the interested companies with a number of subcommittees handles various phases of the problem such as additional generating capacity, transmission lines, system operation, billing, load estimates, etc. These committees pass on all major questions of policy affecting the supply of power.

The four companies supplying the area referred to herein as the Chicago District work together through an Interchange Energy Agreement which has now been in operation for some years. The basis on which it formerly operated was outlined by Mr. E. J. Fowler[3] in 1926. The aim of this agreement, which has since undergone some revisions, is equitably to allocate the following:

1. Demand charges in proportion to maximum demand of each party.

2. Fixed operating charges in proportion to the maximum demand of each party.

3. Fuel charge in proportion to the kw-hr. taken by each party.

Load Schedules

In order properly to distribute the loads, ordinarily two load schedules such as those given in Fig. 4 for the closely linked stations of the Chicago area, and Fig. 5 for the outlying stations are used. These are revised from time to time to take care of varying conditions, such as seasonal load changes and overhauling of one or more units. The essential difference between these two load schedules is that the load schedule in Fig. 4 is fundamentally based on the operation of the distant metering system, as described by Mr. P. B. Juhnke.[4] This is supplemented by some telephone reports and instructions, since Waukegan supply of power to Chicago load is not included in the distant metering system..

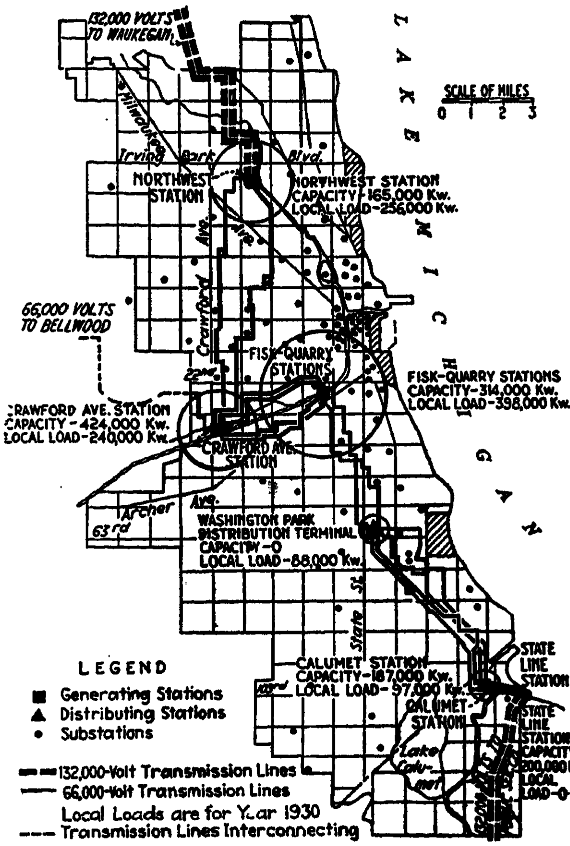

FIG. 2—MAP OF CHICAGO

The advantage of the distant metering scheme is that the principal stations supplying the Chicago load automatically vary the amount that each generates without having to get telephone instructions from the load dispatcher, and furthermore can to a certain extent anticipate any departure in the day's load from the usual load during the season, due to such factors as sudden changes in weather conditions. This is of distinct value when a sudden oncoming storm materially increases the load beyond the usual requirements at the time of the daily noon dip.

Fig. 5 shows schedules for the outlying stations of Powerton and Michigan City. The Powerton schedule gives just the amount to be transmitted into the systems of the Public Service Company of Northern Illinois and the Commonwealth Edison Company and does not give the total amount to be generated at Powerton. In addition the Powerton Station supplies considerable load to the Central Illinois Public Service Company and the Illinois Power & Light Corporation.

Fig. 6 shows for a typical daily load what was the division of load supplied by the principal generating stations, in accordance with the schedules of Figs. 4 and 5.

It has been found practical, as discussed later, to transmit over the 132-kv. lines large amounts of power relatively long distances for this voltage. This can be done only by transmitting this power at practically unity power factor at delivery points, such as Waukegan, Crawford Avenue, and Calumet. It is also to be noted that the send-out voltage at Powerton to accomplish this has to be often 145.2 kv., the maximum operating voltage for the 132-kv. transformers with a

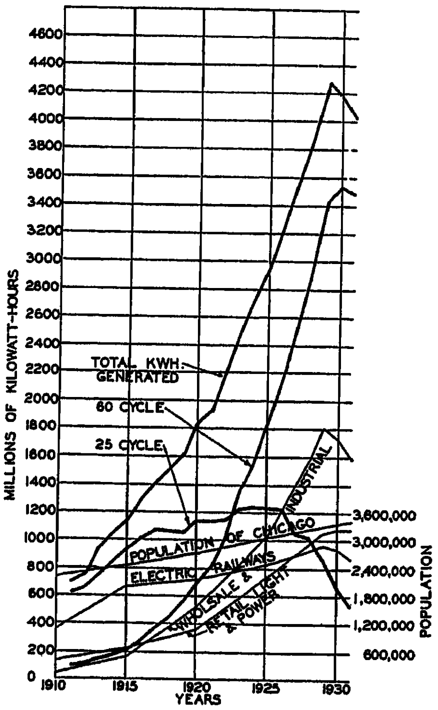

Fig. 3—Growth of Load in Chicago

voltage at the low-voltage delivery points, such as Northwest and State Line of about 125 kv.

At the present time more Powerton power gets into the Chicago District than would occur under usual business conditions when the industrial loads at many of the outlying industrial sections, such as Chicago Heights, Joliet, Electric Junction, Oglesby, and Kewanee would be higher.

Basis of Load Schedules—Increment Fuel Costs

The load schedules that have been discussed are based substantially on the comparative increment fuel costs of the various stations on the system. There are, however, two difficulties in adopting this practise too rigidly.

First: Reserve capacity must be carried at strategic points of the system to take care of emergencies. This is discussed later.

Second: During the early hours of the day from midnight to 4 a.m. and on Sundays and holidays, it is desirable to keep all major stations on the system with some load, and there are certain minimum practical loads that must be carried independent of the economics of the situation.

Fig. 7 gives the comparative increment cost per kw-hr. in per cent, as it varies with the station net output in megawatts for each of the five most recent stations, and also the proportionate cost of coal per B.t.u. The stations near Chicago have substantially the same cost of coal per B.t.u. but between the lowest value of the adjacent stations and the Powerton Station, the most distant station, there is a difference in favor of the Powerton Station of 15 per cent. Consequently in comparing the increment fuel consumption of the Powerton Station with the adjacent stations, not only must consideration be given to the very low fuel consumption for additional loads, but in addition, the advantage of 15 to 20 per cent lower fuel cost must be taken into account.

Neglecting the question of transmission for the moment, it will be seen that to carry an additional 10 mw. on the Powerton Station as compared with Waukegan there would be a differential in favor of Powerton depending on load conditions, but usually at least 33 per cent of the Powerton cost.

Increment Line Loss

The saving in costs due to more economical generation is partly offset by transmission losses. To take proper account of this, increment loss curves must be drawn. The conditions between Powerton and Waukegan are somewhat complicated due to the fact that ordinarily power is taken off at intermediate points such as Dixon, Belvidere, Joliet, and Electric Junction as shown in Fig. 1. To show the effect of the line loss in the power delivered at Waukegan for various amounts of power taken off at these intermediate points, Fig. 8 has been prepared. As stated above, the fuel cost at Powerton is usually 33 per cent less than at Waukegan. Hence, with all fixed charges of transmission to be paid in any event under rental agreements, the increment line loss on Powerton power can be as high as 33 per cent and the power delivered from Powerton to Waukegan, a distance of approximately 240 miles, will have a production cost the same as power generated at Waukegan. If the intermediate load is 60 mw. with the increment loss of 33 per cent, more than 60 mw. can be delivered to Waukegan with the same fuel cost as

that generated at Waukegan. This is slightly below the reasonable stability limit which is shown in this figure by line $L_1 - L_1$, and, under ordinary conditions of operation, will be beyond the generating capacity available at Powerton. Similar studies show it is economical to send power through the State Line Station into Chicago.

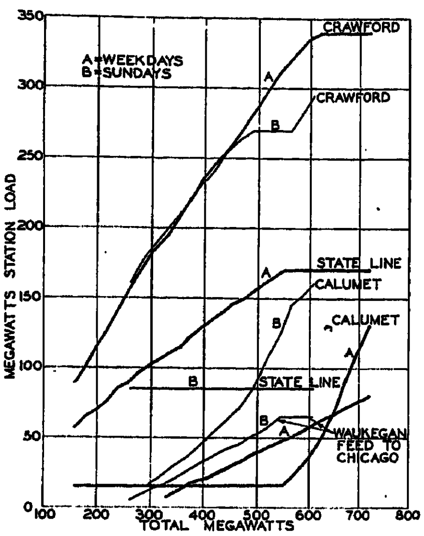

FIG. 4—SCHEDULE FOR MAIN 60-CYCLE LOAD FOR ADJACENT STATIONS—CHICAGO DISTRICT

Usually then the limit in the amount of power coming into Chicago is not the economics of the situation, nor the stability of the lines delivering this power, but instead in the present condition is the capacity available at Powerton for Chicago load.

Within the limits of the stations adjacent to the city of Chicago, that is from Waukegan to Michigan City, the increment line loss is usually not an important factor.

RELATIVE OUTPUT OF GENERATING STATIONS

The result of following the general policies determined from studies such as those outlined above is shown in Fig. 9, which has been made up to show the relative performance of the stations, the output and the per cent of the total load carried by each for the year 1931.

It will be noted that the Chicago territory, as a whole, produced 100 per cent of its power at an average B.t.u. per kw-hr. send-out of 15,006. Of this power 85.8 per cent was produced in stations with an average B.t.u. of 13,910. The capacity of these stations in per cent of the total capacity was 58.3, although, as stated above, they produce 85.8 per cent of the kilowatt hours. Older stations produced only 14.2 per cent of the power with an average B.t.u. per send-out of 21,603, although their capacity in the per cent of the total capacity was 41.7 per cent.

Of the 25-cycle power used in Chicago about two-thirds is generated at 25 cycles and about one-third is generated at 60 cycles and transformed through two 40,000-kw. frequency changers with a loss of about 6½ per cent. While the latest 25-cycle generating apparatus, of which the last unit was installed in 1920, has a B.t.u. per kw-hr. send-out of about 19,000 as compared with about 14,000 average for the 60-cycle generating apparatus, studies show that the 25-cycle generating apparatus cannot yet be replaced with new 60-cycle generating apparatus, because the fixed charges on this new generating apparatus, when added to the operating charges even at an economy of 12,000 B.t.u. per kw-hr. will give total charges on the new greater than the operating charges on the old apparatus. Also since the kw-hr. generated at 25 cycles is rapidly decreasing, the fuel consumption for this class of service is every year becoming a less important factor in the average production cost for the Chicago load.

A consideration of Fig. 9 will show the great advantage of interchange energy contracts and purchase contracts so drafted as to give all parties concerned the maximum practicable and equitable benefit of the most efficient stations. The same situation exists in the possibility of savings between central stations and large industrial plants.[5]

PROGRESS IN STATION ECONOMY

Beginning with the installation of 300-lb. steam turbines which went into operation at the Joliet Station of the Public Service Company of Northern Illinois in 1917, the principal factors that have improved the thermal efficiency in stations of the Chicago District are the following:

1. Increased steam pressure
2. Increased steam temperature
3. Reheat
4. Regenerative cycle
5. Pulverized coal furnaces

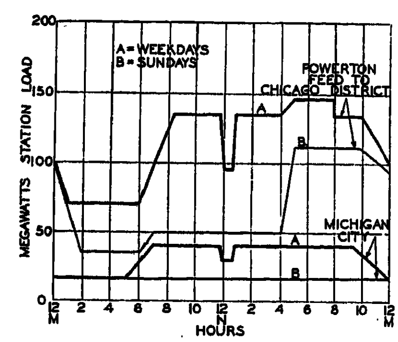

FIG. 5—SCHEDULE OF LOAD FOR DISTANT STATIONS—CHICAGO DISTRICT

It must be borne in mind in comparing these economies with those obtained in stations of the east, particularly in those burning a better grade of coal than is used in the Chicago Region stations, that the Illinois coal runs about 12 to 15 per cent ash and 12 to 15 per cent moisture. The use of pulverized coal was under

consideration for many years in the Chicago District, and as soon as actual experimental boilers installed at Calumet Station had shown that furnaces capable of burning this coal successfully were available, they were adopted for use in the Chicago Region stations.

Table II gives the dates of operation of units with these improvements in the Chicago District.

TABLE II—CHARACTERISTICS OF 550—650-LB. UNITS IN CHICAGO DISTRICT

Year in service	Station	Unit	Mw.	Gen. voltage	Throttle steam pressure lb/sq. in.	Throttle steam temp. fahr.	Reheat	Boilers
1924	Crawford	2	60	12,000	550	725	Boiler	Ch. grate
1925	Crawford	1	51	12,000	550	750	Boiler	Ch. grate
	Crawford	3	50	12,000	550	725	Boiler	Ch. grate
1926	Crawford	4	75	12,000	550	750	None	Ch. grate
1927	Waukegan	3	50	12,000	600	725	Boiler	Ch. grate
	Crawford	5	88	12,000	550	750	Steam	Ch. grate
1928	Crawford	6	100	12,000	550	725	Steam	Ch. grate
	Powerton	1	52	22,000	600	725	Boiler	Pulv. fuel
1929	State Line	1	200	22,000	650	730	Steam	Pulv. fuel*
	Powerton	2	52	22,000	600	725	Boiler	Pulv. fuel
1930	Waukegan	4	65	12,000	600	725	Boiler	Pulv. fuel
	Powerton	3	100	22,000	600	725	Boiler	Pulv. fuel
1931	Michigan City	1	68	22,000	650	750	Boiler	Pulv. fuel
	Waukegan	5	115	18,000	625	750	Boiler	Pulv. fuel

*Now uses 70 per cent dump gas.

Fig. 10 shows the improvement in the economy of the stations to the Chicago District for the years 1925 to 1931, inclusive.

The relative improvement due to advance in turbine and boiler design is shown in the case of the State Line Station. The unit 1 turbo-generators have an efficiency about 4.5 per cent better than that of the next previous units in the Chicago District, but the change from chain grate stokers to pulverized fuel equipment, together with that improvement in turbo-generator efficiency, made a total gain in efficiency of 10.4 per cent, reducing the B.t.u. per kw-hr. send-out for a period of a month or longer from about 14,500 to about 13,000. The 1,200-lb. No. 2 and No. 3 units on order will have a turbo-generator efficiency of about 11.5 per cent better than No. 1 unit, and the expected overall B.t.u. per kw-hr. will be reduced from 13,000 to 11,500 B.t.u.

Economics of High-Pressure Steam

The tables and diagrams referred to above indicate the great economies effected with high-pressure steam and other improvements. Table III has been made up to show the increase in capital expenditure that will be offset by these savings in operating costs, and produce power for the same total cost including all charges.

The 600-lb. stations, as shown in this table, ran at an average capacity factor in 1931 of 53.2 per cent and produced the average kw-hr. sent out for 13,900 B.t.u. The saving in fuel costs shown in Table III has been made up with a variety of coal costs, so that the effect of changes in this figure, which varies considerably with conditions, will be apparent. The table gives the saving in the 600-lb. stations, as compared with a 350-lb. station on a capacity factor of 53.2 per cent mentioned above. Also it is apparent that as the 600-lb. equipment gets older it will naturally run at a lower annual capacity factor, but there seems to be no reason to believe that during its useful life its capacity factor in a large interconnected system need be less than the average in the Chicago system for the last ten years, which was 39.5 per cent. Therefore, the saving per year over its life should be at least from $1.18 to $2.36 per kw., justifying the expenditure to obtain this of from $10.75 to $21.50 per kw., based on 11 per cent fixed charges, and still give the same total overall cost of power.

TABLE III—1931 OPERATION OF 550—650-LB. UNITS

Station	Millions kw-hr. sent out	Thousands kw. capacity	Capacity factor	B.t.u. per kw-hr. sent out
Crawford Ave	1,880.4	424	50.6	14,914
Powerton	1,173.9	204	65.5	12,679
State Line	1,009.5	200	57.5	13,446
Waukegan	535.0	153.3(A)	31.9	13,890
Michigan City	269.8	58.5(A)	52.4	14,238
	4,868.6	1,039.8	53.2	13,900

(A) Average. One unit began service during year.

B.t.u. per kw-hr., average	13,900
B.t.u. per kw-hr. on 350-lb. units	17,500
Gain in 550—650-lb. units, B.t.u. per kw-hr	3,600
Coal, B.t.u. per lb	10,500
Gain in lb. coal per kw-hr	.343

Coal cost $ per ton	2.00	2.50	3.00	3.50	4.00
Capacity factor 53.2% (average of 550—650-lb. units)					
Hours operation	4,700	4,700	4,700	4,700	4,700
Saving per kw. per year	$1.61	$2.02	$2.42	$2.82	$3.22
Permissible increased investment per kw. at 11% fixed charges	14.70	18.40	22.00	25.70	29.40
Capacity factor 39.5% (average of Chicago District)					
Hours operation	3,460	3,460	3,460	3,460	3,460
Saving per kw. per year	$1.18	$1.48	$1.78	$2.08	$2.36
Permissible increased investment per kw. at 11% fixed charges	10.75	13.45	16.13	18.90	21.50

Still greater economies than those outlined above are expected from the 1,200-lb. equipment now on order for the extension to the State Line Station, which should produce a kw-hr. for 11,500 B.t.u.

Frequency Control

An important factor in the economical operation of the system is the method of frequency control in use. At the present time it is the normal practise to have Windsor, Philo, and Springdale Stations in the east under automatic frequency control, and when the tie line from Michigan City to South Bend is closed no automatic control is in service in the Chicago District. When this tie is open usually an automatic frequency controller at the Crawford Avenue Station is in service on one or two units, allowing the remaining stations to follow scheduled load. The former method of frequency control has, under normal conditions, held the frequency correct within 1/20 cycle and the time drift to about 2 seconds, with the eastern system connected with the western.

Wattless Kva., Voltage, and Phase Angle Control

Apart from generating station economics it is necessary to get the most efficient operation of the transmission system. The use of voltage and phase angle

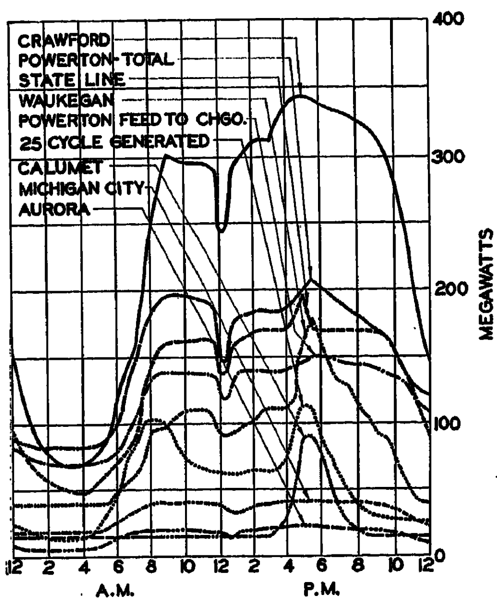

Fig. 6—Station Load Curves

control here is of great assistance. Most of the 66-kv. and 132-kv. transformer banks in Chicago and at the distant generating stations are provided with load ratio control designed for a variation of plus or minus 10 per cent in voltage.

These tap changers under load also serve the purpose of controlling wattless kva. on the lines, and in one case at least this has permitted carrying regularly an appreciably higher kw. load on a set of cable ties by operating the heavily loaded cable at unity power factor, and allowing the wattless kva. to be carried on the other cables with more margin in capacity.

It is of interest to note that the charging kva. of the overhead lines and also of the cables has a considerable effect on the power factor of the system. The charging kva. of the 132-kv. lines amounts to about 55 mva. and of the cable system about 83 mva. In addition there is a synchronous condenser capacity of more than 60 mva. Also in Chicago proper the 60-cycle rotary converters on the interconnected system of approximately 96 mw. are of assistance.

All these elements that tend to produce a good power factor, together with the normally high power factor of the metropolitan load of Chicago at the peak, enable large quantities of power to be brought into the city at high power factors without the use of large rotary condensers in Chicago.

With the installation of units 2 and 3 at State Line, phase shifters under load to give a displacement of 5.8 degrees will be used on the new 100-mw. 66-kv. feeders to the Commonwealth Edison Company to assure their carrying full load when in parallel with 60-mva. feeders.

Reliability

There are two phases of the problem of reliability: first, the design of the individual stations, equipment, and transmission lines so as to reduce the possibility of outage; second, the operation of the system in such a way that any outage will not interfere with the supply of power to the consumer.

Design for Reliability

There is constant pressure on the designing engineer to reduce the first cost. Great savings could be effected in both generating station and substation design by sacrificing reliability, but this is not desirable. In power station design there is a definite limit to the cost in dollars per kw. if reasonable reliability is to be maintained.

Generator Design

All recent 60-cycle generators in the Chicago District were for 12,000 volts until in 1928 the Powerton Station began operation with a 52-mw. 22,000-volt generator, the first generator of that voltage to operate in the Western Hemisphere. There are now in the Chicago District 7 generators with 22,000-volt windings and 1 of 18,000 volts. At the time of writing this paper, none of these generators has given any insulation troubles. It might be mentioned that in none of these installations are there any outgoing feeders at generator voltage. The 8 units are of three different makes, are in four different stations, have the equivalent of about 17 generator years of service, and have demonstrated the entire success of high-voltage windings for generators. The aim has been to reduce the current necessary to handle in generator main cables and generator oil circuit breakers.

At State Line Station the 200-mw. unit is of the triple compound type giving the reliability of a two-unit station. This unit can continue to turn out power with

any one or two members out of commission, except in the case of both low-pressure members. Since December 19, 1929, the unit has been supplying power continuously to the system, and the high-pressure member has run continuously for as long as 81 days.

Switchgear Design

The most outstanding developments from the electrical point of view in Chicago territory have been the use of isolated-phase and metal-clad switchgear.

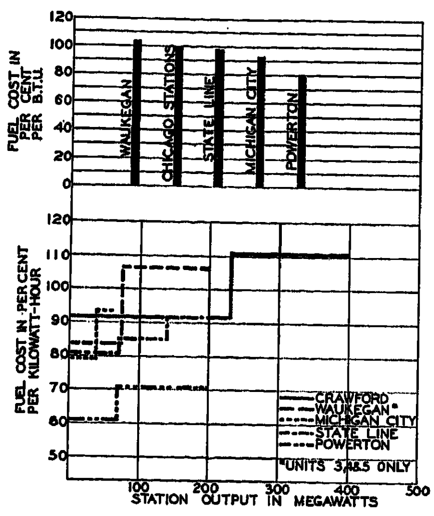

Fig. 7—Increment Fuel Costs

The importance of the Crawford Avenue Station in the Chicago District made advisable the further use of the isolated-phase principle, which had been first used at Calumet. This is now applied throughout the Commonwealth Edison system not only to 12-kv. equipment but also to 66-kv. outdoor equipment. The record of the Crawford Avenue Station has in the seven years of service demonstrated that a high degree of reliability has been attained by its use and faults confined to phase to ground in both 12 kv. at the station and 66 kv. on the system. The following points in design are to be noted as important factors in this record:

1. Fault bus protective scheme.
2. Reactors in all connections from generator buses.
3. Phases isolated at generator voltage and 3-ohm resistor in the neutral connection of one generator at a time.
4. Phases isolated at 66 kv. with circuits of single conductor underground cable and 30-ohm resistor in transformer neutral.

In addition to isolated-phase indoor and outdoor switchgear for 12 kv. and outdoor for 66 kv., the last four years have seen the rapid application of metal clad switching for 12 kv., 22 kv., 33 kv., and 132 kv.

In 1927 compound-filled indoor metal clad gear was used on the 12-kv. bus of unit 3 at Waukegan. In 1928 the first experimental outdoor metal clad equipment with oil-filled buses was installed at the Wheaton substation of the Public Service Company of Northern Illinois. This was followed by 22-kv. outdoor metal clad gear on the main generator bus at State Line and Powerton, additional 33-kv. substations, and in 1931 132-kv. equipment on unit 5 at Waukegan.

The chief advantages of metal clad gear are the following:

1. Personal hazards are practically eliminated.
2. The metal enclosed buses reduce the possibility of phase-to-phase short circuits.
3. Outdoor equipment eliminates building costs.
4. Factory assembled equipment reduces installation costs.
5. Fault bus protection is applicable for quick clearing of faults.

In 3 years of operation of the State Line Station, where the station auxiliary equipment is indoor metal clad and the main bus is outdoor metal clad, no member of the entire operating staff has met with any electrical personal injury accident of any kind. Also during this period with about the maximum range of temperature attainable at Chicago, the State Line metal-clad gear has developed no serious problems and the only minor difficulties encountered are those inherent in any electrically operated mechanisms whether installed indoors or outdoors.

The success of such equipment in the system of the Public Service Company of Northern Illinois has been outlined by Mr. J. L. Hecht of that company.[6]

Transmission Line Practise

The experience with high-tension cable installations in Chicago has shown the very satisfactory perform-

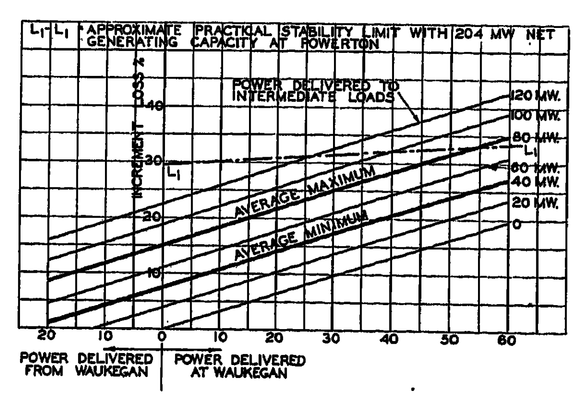

Fig. 8—Increment Loss Curves—Powerton—Waukegan

ance that can be obtained with hollow core oil-filled cables as used in 132 kv. in service since 1927 or solid-core single-conductor cables provided with oil pressure reservoirs on 66 kv. in service since 1926. The use of oil reservoirs has also been adopted on the 22-kv. single-conductor cables at State Line and Powerton since they form part of the generator bus as it was felt that the additional cost was small and maximum reliability was essential. No cable failures have been experienced at

either of these stations. The record of the 66-kv. and 132-kv. underground cables is annually given in the reports of the N.E.L.A. On overhead lines the greatest advance in reliability has been effected by the use of ground wires. The first few years service of 132-kv. lines was summarized by Mr. E. C. Williams[7] and further experience has confirmed the improvement outlined in his summary.

Relay Protection

The relay scheme of the territory is of the greatest importance in matters of reliability since it is very necessary to clear a short circuit in the minimum time.

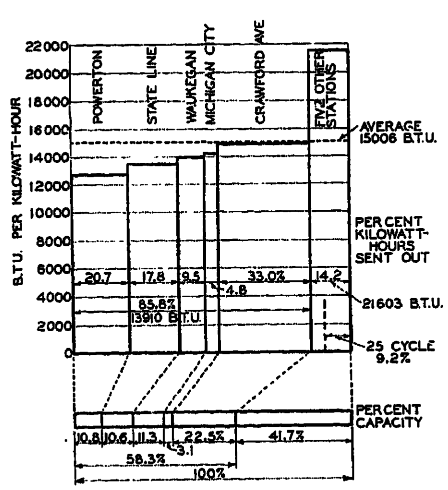

Fig. 9—Economies of Generating Stations

On all the 66-kv. cables in Chicago a reliable pilot wire protection scheme is used which opens the breakers at both ends of the line simultaneously in case of unbalanced ingoing and outgoing current in the line.

On the 132-kv. system the usual type of over-current and directional relays was used up until 1930, when because of the long time that was obtained in cascading, these were replaced by distance relays operated in certain cases by fault-detector relays. These distance relays take care of phase-to-phase short circuits. For line-to-ground faults, directional ground relays are used connected in the neutral of the power transformer banks, which are solidly grounded at all stations. In order to facilitate proper relay operation throughout the territory an Intercompany Relay Committee is in charge of relay settings, and recommends changes in types of relays so as to get the most satisfactory operation from the system.

Operating to Insure Reliability

The fundamental object in planning for system reliability is to operate in such a way that trouble in one section will not be allowed to spread to a large area, and also to provide sufficient reserve capacity to take care of any emergency.

The basic scheme which has been used in feeder arrangement has been a natural consequence of the isolated-phase idea. While in the station the various phases are kept separate, so that trouble will not spread from one to the other, in the system the transmission lines are divided into several sections so that one can be lost without affecting the load. In Chicago the 66-kv. cable system extending through the city from north to south is divided into two systems called the Red and Blue.[8] These are kept quite separate on the 66-kv. side and tied together only on the low-tension side of the step-down transformers at the various distribution centers. This means that the load will never lose supply, and trouble that might occur on one 66-kv. bus at any station will involve only part of the system.

The same thought has been carried out in the supply from Powerton. It can be seen from Fig. 1 that there are three routes to Chicago, each about 200 miles long. These are operated as three separate systems known as the Red System through Kewanee, Oglesby, Joliet, Electric Junction, Crystal Lake to Waukegan; the Green System through Kewanee, Dixon, Belvidere to Crystal Lake to the north; and the Blue System through Kewanee, Oglesby, Joliet, Chicago Heights to State Line. Each system has its own generator at Powerton. Since it has been found economical to feed as much power as possible from Powerton it is the practise to load these lines well up to a point not far from the stability limit, which represents about the full available

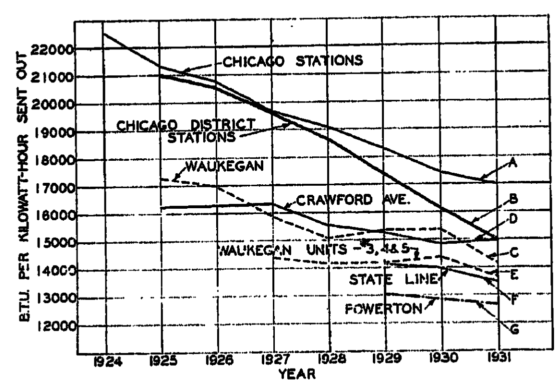

Fig. 10—Yearly Averages of Heat Rate—Chicago District

output of the Powerton Station. If all three systems were bussed at Powerton the total supply from Powerton would have to be reduced in order to ride through short-circuit conditions.

In the case of Waukegan, also, a loss of both lines to Chicago would be serious. It is therefore the practise usually to operate those lines separated, with one or more generators on each 132-kv. line to Chicago, and Powerton supply connected to only one section.

Reliability is further insured by the 132-kv. connection to the east tying in with the system of the American Gas & Electric Company. While there is normally little

transfer of power between the two systems there is some mutual assistance in case of trouble on either system.

Reserve Capacity

From the above it can be seen that consideration must be given to the possibility of certain line failures that would cause a loss of generating supply to Chicago. It is estimated that the maximum to be expected would occur in case of interruption of one of the lines from Waukegan to Chicago when there would be a loss of not only the machine on that line at Waukegan but also the Red and Green feeds coming through Waukegan from Powerton. This would be a maximum of about 90 mw. It is to be noted that this is little different from the loss of the largest unit within Chicago itself. Arrangements are made to have this amount of reserve capacity running on the stations of the Chicago District so that the load can be picked up without difficulty. It is apparent therefore that the total reserve is practically independent of the load on the system, but is dictated more by the size of generating units and tie lines. In all recent units the most economical point of operation is about three-quarters load, so that a reserve is available without loss of efficiency. This is shown in Table IV.

TABLE IV—RUNNING RESERVE IN CHICAGO DISTRICT IN MEGAWATTS

Adequate Boiler Capacity to Supply Same Must Be Kept Available

Week Days		Sundays
30 mw.	Crawford	30 mw.
10 mw.	Calumet	10 mw.
15 mw.	Fisk	10 mw.
15 mw.	Northwest	10 mw.
20 mw.	Battery	10 mw.
15 mw.	State Line	15 mw.
15 mw.	Powerton	15 mw.
10 mw.	Waukegan	10 mw.
6 mw.	Michigan City	6 mw.
Total... 136 mw.		116 mw.

On one occasion in which the entire supply from Waukegan and the Powerton Red and Green systems into Chicago was lost, the load was picked up with a momentary drop in frequency of only 4/10 cycle and no interruption in service to customers at any point.

Conclusions

From the practises outlined above the following general conclusions may be drawn:

1. When several companies are as closely linked as those in the Chicago territory, some working agreement must be established to produce the best overall economy of the system, as well as benefits of that economy to each party.

2. The most efficient types of equipment should be installed as rapidly as they become commercially available.

3. For any power station for a large interconnected system, there is a standard below which sacrificing efficiency produces no improvement in reliability, and reducing fixed charges at the expense of operating efficiency will increase the overall cost of energy. Furthermore, as manufacturing technique improves, this standard is continually advancing.

4. There has been a marked gain in economy by increasing steam pressures and temperatures without reduction in reliability.

5. The first unit or two built for higher pressure than has been previously employed does cost appreciably more per kw., but the third or fourth at the higher pressure costs appreciably no more per kw. than those of the lower pressure. The result then is that the average increase in cost for the four units is usually more than offset by the economy in fuel costs produced thereby. In periods of depression, such as the present, the efficient units are able to produce a far greater percentage of the total output than if the system is loaded to capacity, with a result that the saving in fuel costs more than offsets the increased fixed charges necessary to produce same.

6. Broad generalizations about the cost of power stations, or even of their operating costs, are of little value, because each one is a problem in itself. Both construction and operating costs are very considerably affected by location, which to a large degree determines such important factors as kind, character, and cost of fuel, type of foundations, extent of ground improvements, as well as by characteristics of the electric load, capacity factor, and amount of plant reserve required. The economic balance between the operating costs and fixed charges on the investment must be analyzed separately for each case.

7. It is recognized that interconnections of such different loads as electric railways, large industrial factories, and retail light and power in the same area from the same power supply has produced notable economies from diversity in load characteristics. Interconnection of large areas has produced still further economies from diversity in load.

8. The experience with the 132-kv. cable, which so far has been absolutely reliable from the electric failure standpoint, indicates that 220-kv. cable of ample reliability is feasible, so that in the choice of underground cable, economics rather than reliability largely dictates the choice of voltage.

9. With modern overhead steel tower transmission lines, skilfully constructed with low-resistance grounds, reliable ground wires, and coordinated relay protection, experience has shown that increasing amounts of power can be transmitted into Chicago without decreasing the reliability of supply to the distributing centers.

10. Load schedules for station output should be set up based on increment fuel costs, reliability, and reserve capacity.

11. Totalizing schemes for load dispatching are of considerable assistance in efficient operation of the system.

12. Automatic frequency control is a distinct advantage in conjunction with distant metering in enabling the individual stations to readily adhere closely to predetermined schedules.

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13. "Power Flow Studies in Interconnected Systems," P. B. Juhnke, *General Electric Review,* December, 1930, p. 670.

Discussion

I—COMBINED RELIABILITY AND ECONOMY IN OPERATION OF LARGE ELECTRIC SYSTEMS—THE DETROIT EDISON COMPANY
(Fugill)

II—THE EDISON ELECTRIC ILLUMINATING COMPANY OF BOSTON
(Dillon)

III—PHILADELPHIA ELECTRIC COMPANY SYSTEM
(Anderson and Estrada)

IV—CHICAGO DISTRICT
(Perry and Smith)

R. L. Thomas: The paper of Messrs. Anderson and Estrada is of particular interest to anyone connected with a combined hydroelectric and steam-electric generating system and is a valuable contribution to technical literature, particularly with respect to the division of load between a run-of-river hydro plant and steam generating stations.

An interesting and complex phase of load division between steam plants and a run-of-river hydro plant with pondage is the economics of weekly drawdown—*i. e.,* a gradual drawing down of the pond say from Monday morning until Friday evening or Saturday, with a refilling over the week end. It is possible that the authors' omission of discussion of this is due in part to the fact that in the future, Conowingo operation in this respect will depend in some measure upon the method of operating the Holtwood and Safe Harbor developments on the Susquehanna River immediately above Conowingo. The Holtwood plant was first placed in operation in 1910 and now has a capacity of 111,000 kw. The Safe Harbor plant, which is thoroughly described in a series of papers presented at the Baltimore District meeting has an initial capacity of 168,000 kw., and was brought into service during the past few months.

The operation of the Holtwood plant of the Pennsylvania Water & Power Company in the combined Baltimore-Holtwood system has been described in several contributions to the technical societies. In general, the operation has been similar to that described for Conowingo, with the hydro plant carrying the peak loads during low flow, thus giving the Baltimore and Holtwood steam plants a "flat" load, and carrying the base load during periods of ample flow, with the steam plants taking the peaks. The Holtwood pond is too small to make weekly drawdown economical and it has been the practise to have the pond full every morning. However in hypothetical analysis for determining system generating investment programs weekly drawdown has been assumed. Set-ups were made to determine the maximum peak service or demand value obtainable from the hydro plant in case of the very unlikely occurrence of what has been dubbed the "pinch power condition"—*i. e.,* the coincidence of minimum river flow, maximum load and break-down of the largest generator units.

With the Safe Harbor plant in operation above Holtwood the problem has become much more complicated. The combined effect of greater area of pond, higher efficiency of generation and slightly better average head is that one foot of drawdown at Safe Harbor will yield about three times as much energy as one foot at Holtwood. Due to the "lapping" of heads a drawdown of the Holtwood pond is partially recovered in the form of increased head at Safe Harbor. On the other hand the Holtwood tailrace elevation is influenced by the amount of power house discharge to a much greater extent than the Safe Harbor tailwater. There are other practical considerations which affect the division of load between Holtwood and Safe Harbor, such as the fact that Holtwood supplies Baltimore at 25 cycles and Safe Harbor at 60 cycles, the amount of frequency changer capacity available, etc. Exhaustive studies which depend in part upon practical experience and the result of efficiency tests are in progress to determine the proper division of load between the two hydro plants. Investigation is also being made to determine to what extent weekly drawdown of the Safe Harbor pond is economical. Such drawdown, of course, results in a decrease in head and a loss of output at the Safe Harbor plant, but this may be more than offset by savings at the Baltimore and Holtwood steam plants—particularly a decrease in boiler banking losses. A possible method of operation is to give the steam plants a uniform flat load throughout the week, including Saturday and Sunday. It is more likely, however, that the "steam line" should be a horizontal line from Monday to Friday, but lower on Saturday and Sunday. It also appears probable that even on any one day, due to the relative characteristics of the Baltimore steam plants, the steam line should be a stepped line rather than a single horizontal line.

It may be of interest to state that for the seven days June 7th to 13th inclusive the weighted average daily load factor of the Baltimore steam plants was 95.9 per cent. The weekly load factor was 87.0 per cent. The Safe Harbor pond during this period was drawn down about 3½ ft. It is possible, however, that the studies will show that lower steam plant load factors would have been more economical.

It appears probable that the Holtwood pond should not participate in weekly drawdowns but should simply pass along to Conowingo the daily in-flow received from Safe Harbor. It follows that the operation of Safe Harbor plant as to weekly drawdown will influence to a great extent the operation of the plants below Safe Harbor.

The statement in connection with determination of investment programs that "accurate forecasts of the future loads are essential" raises a number of questions which may, under present conditions, border on the realm of speculation but which might well be the subject of engineering discussion and investigation.

Going back to the halcyon days of 1928-1929 no doubt every power company made forecasts of load for several, or even many, years ahead. When the depression came the residential and commercial load at first continued to grow, but the industrial load fell off. It was then the opinion of many operators that with a return of normal business conditions the recovery of industrial load, superimposed on the continuous growth of residential load, might bring about an abnormal rate of increase which might catch some companies unprepared. More recently, however, the residential and commercial load has ceased to grow or, in many cases, has actually decreased. What then may we expect in the future? Is the decrease in residential load due primarily to a practical cessation of new connections and an abnormally large number of cut-offs? To what extent have householders attempted to economize in the use of electricity? When growth in total load is resumed will it be at the previously normal rate, resulting in a shift of the load curve or a postponement of loads, or will the growth be at an accelerated rate tending to cause the load to "catch up" with the former estimates? The writer is inclined to think that, under present conditions, any forecaster who predicts loads for even a year or two in advance with "an error of only 2 or 3 per cent" may consider himself fortunate.

J. B. Baker: These papers well describe present methods of power system planning and operation and deserve a fifth or summary paper analyzing their similarities and differences. Within the last ten to twelve years, the subject of power generation has greatly broadened, so that one can no longer survey it without a comprehension of the relations within a group of stations. The development of interconnection has modified operating practise by bringing in aspects beyond that of the single power station, or a compact group of power stations. It is apparently not however, producing a widely connected geographical power scheme as was forecast by some of its early proponents. Instead the papers tend to show that the main reliance for power supply in any load area will continue to reside in power stations adjacent to the load. The true function of interconnection therefore seems to be of a supplementary nature.

Relatively long distance transmission of large blocks of power would seem from the papers to be limited to instances where hydro power is available at an attractive overall cost, and in the case of the Powerton station, where a low cost of fuel occurs in conjunction with a high fuel economy. The papers however substantiate each other in indicating that, at least in this part of the country, transmission from remote centers of production is wholly supplementary to local sources of supply in volume and operating reliability.

An interesting possibility that is appearing in the design of power stations is the unit plan of generators and boilers. The present papers lead one to anticipate that the adoption of the unit plan will in no way compromise operating reliability. Future papers on this subject will be welcome.

It is significant that the papers show a continued improvement in operating economy during the past two years despite a falling off in system load. It is understood that operating practises have played a large part in this continued improvement.

All of the current ideas regarding design specifications and operating practises to the end of reliability and operating economy, including purchased power commitments, are mentioned in these papers, and the student of the subject will be fully repaid for whatever critical analysis he may make of them.

Carl M. Gilt: The papers illustrate the progress that has been made toward securing continuity of service for each customer and the system as a whole. Equipment has been improved, lessening the frequency at which it fails, and systems and stations are sectionalized so that ordinary failures are limited in their effects. Much of this has been secured at little or no increased cost, and a certain amount of sectionalization has been adopted, partially at least, as a means of reducing costs.

However, there are failures, which fortunately are rare, but nevertheless are within the realm of possibility, which might very well result in the complete shut-down of a generating station. Such failures might be the rupture of a large steam line almost instantly filling the boiler house with steam, or a high pressure boiler feedwater line, or in the electrical end, a serious fire or explosion, possibly involving the control system. The fact that the community is fed from two or three stations may not greatly relieve the situation even though there are adequate ties between the stations. The sudden increase in load on the remaining stations of 100 per cent or even 50 per cent of what they were carrying, would, in many cases, be beyond the capacity of boilers, turbines, and generators to pick up quickly. Such a failure in a densely populated Metropolitan area would be a catastrophe that none of us would care to pass through.

There are two methods of more or less successfully meeting such a situation, after all reasonable precautions have been taken to avoid a complete station outage. The first divides the territory into sections, each fed by its own station, with ties to other stations for economy and ordinary contingencies, but designed with the intent that they shall open in serious emergency so that the failure of one station will not take others with it. The most important parts of the territory may be fed from the several sources and so limited in extent that the failure of one supply will not endanger the others.

The other method makes use of a high-tension network fed from so many sources of such relatively small capacity, that the complete loss of any station will not impose more load on the remaining stations than they can promptly pick up. It is essentially a system of decentralization of power supply with the high-tension network, a pool into which power is poured and from which it is drawn. Obviously, the network must be made up of such relatively small parts and so designed that an extended failure or break-up is inconceivable. While wide physical separation of stations is desirable it may not be practicable, but it is essential that the various "stations" be so completely isolated that any failure in one cannot communicate to another.

At first thought, costs of such a system may appear high; however, for the larger systems, such stations are of the order of magnitude of 500,000 kva. and make use of the most economical sized units available. Such stations frequently tax outlet facilities to the maximum so that larger concentrations of power may actually increase the cost per kw. of station and outlets. With feeders laid out primarily to cover the area served, not radially from each station, but essentially as a loop system, running from station to station, and load tapped off at intermediate points, the addition of new units or stations is accomplished essentially by cutting into an existing moderate voltage distribution system with but little additional line investment. Some difficulties may be experienced in securing proper division of load between lines, but these can be met by carefully distributing load among the feeders. It would appear that such a system would carry through any catastrophe short of one that would also wreck the community along with the electric system.

Philip Sporn: Previous to a year or so ago many power systems were taxing their production and transmission facilities to the limit to keep up with the heavy and increasing load conditions. The problem of design frequently centered about the question as to how soon additional facilities could be brought on the system and too frequently not enough attention was given toward bringing about a proper balance between cost and reliability. During the last year, however, many systems have been confronted with the problem of bringing about operating economies and have had to face the question as to how well the various parts of their system fit together with a view of permitting the

maximum operating economies. They have had an opportunity to analyze some of the capital expenditures involved in making these extensions and re-evaluating the wisdom or the lack of wisdom of some elaborate features that were incorporated as part of the design.

From the system planning standpoint such an analysis ought to be particularly fruitful. With the decrease in load experienced on many systems it ought to be possible to check whether the system in the light of present conditions is still flexible and reliable enough to permit maximum utilization of the most efficient equipment—shutting down complete generating stations if necessary, and serving by transmission lines the entire load of areas formerly served direct from generating stations. If the system has been properly laid out, this economy ought to be possible without any appreciable sacrifice in reliability of service. Minor improvements or alterations, such as the speeding up of breaker operation to reduce the time required to clear faults, might be required before embarking on such a generation and transmission program but the main backbone of the system ought to be there to permit such a change in operating conditions. If the system lends itself to such operation, it has been well planned.

In our own case, under present conditions, many sections of territory that under more favorable load conditions were supplied by their own generating plants, are being handled strictly on a transmission basis. In this connection, it ought to be pointed out that whereas an economical limit to transmission of power is a very definite thing when cost of transmission and regulating facilities are taken into account, this limit automatically disappears once these facilities are already in and the question of their fixed charges plays no part in the picture. In other words, with the transmission facilities an established fact, the electrical transmission *versus* say the railroad transportation of coal has a much greater advantage and it is possible to transmit frequently hundreds of miles even at moderate voltages and obtain great economies over the equivalent rail transportation.

In connection with the question of increased economy and reliability, the proper method of attack in each case is to weigh all the conditions and not go after any additional economy unless there are definite indications that the operating savings will justify all the increased capital expenditures. However, it must not be forgotten that excessive cost per kw. of installed capacity and resulting economy need not necessarily be synonymous. It is entirely possible by eliminating, in many cases, the fancy fittings, architectural, mechanical and electrical, which are frequently allowed to go into a plant, and spending some of these savings in the form of high grade economical equipment, to not only get a highly economical plant, but to obtain it also at a very reasonable cost per kw. This is not to be taken as advocating a class of architecture in which ugliness is predominant; but it is worth while to remember that the object of a generating station is to supply kw. and generate kw-hr., and that the utilitarian motive ought to be predominant in all of its planning and designing.

Again, an analysis such as given in some of the papers should be particularly fruitful in determining the actual economies of some of the very elaborate features that were introduced in their construction. For example, in Mr. Dillon's paper it is stated that it has been his company's policy to duplicate auxiliaries to turbines and boilers, safeguarding against all emergencies, and while this has yielded a high cost per kw. of capacity, it has been justified because there has never been a loss of load due to either lack or loss of generating equipment. Of course, this does not mean that the same conditions might not have prevailed even without going to this duplication of facilities. Mr. Dillon states, it is true, that the policy of some other companies, with simpler installations and with a greater number of spare units, is being watched, but I do not see any comment upon the possibility of eliminating *all of these duplicate or spare features entirely* and relying upon the inherent and natural diversity between the various parts of the interconnected system and letting the interconnected system take care of such major (if any) catastrophe to prevent loss of load. Admittedly interconnecting a large group of power companies involves an expenditure of many millions of dollars, yet how can all these expenditures be justified if this splendid machine consisting of the interconnected system is not utilized at the very time when it can pay the most handsome dividends, namely in times of major distress?

On our own system we have had occasions where 100,000 kw. or more have been dumped on the interconnected system and while the system may have groaned slightly, it handled the load in most cases. Further, the giving or the receiving of aid has not been confined to any one particular section of the system, it generally happening that the company that needed aid at one time is the one that made possible the giving of aid to another of the group the very next time.

In connection with the same subject of reliability and cost, Mr. Fugill's comment with regard to the d-c. drive of auxiliaries is of interest. Mr. Fugill states that in his company d-c. drive of all auxiliaries has been justified by records which showed that there is little cost advantage for the a-c. system. This does not check with the great many studies that we have made on the same subject. Of course, if adjustable speed is called for in almost all drives, this may be the case, but here again our studies have shown that in very few applications in a power plant is adjustable speed drive really justified and on that basis the economies are most certainly in favor of the a-c. system. It would be very interesting if Mr. Fugill could furnish some information showing that the d-c. drive is almost as economical as the a-c. drive.

These papers mention some of the various ways in which interconnections are made use of to the fullest extent. In the case of one of our properties, which has a high seasonal summer peak, an arrangement is made annually with one of the interconnecting foreign companies under which our company receives 10,000 kw. standby without any charge during the period of June 15 to September 15, and furnishes a corresponding amount of standby to the other interconnecting company during the period of November 1 to February 1, the period when this other company invariably has its peak. This is cited as a very interesting case in which advantage is taken of seasonal diversity.

Messrs. Anderson and Estrada indicate the economy at the Deepwater Station as compared to the rest of their system. This, station is owned jointly by the Philadelphia Electric Company and the Atlantic City Electric Company, one of the subsidiaries of the American Gas and Electric Company. It may be of interest to give some actual data regarding the results obtained to date at the Deepwater Plant.

The average B.t.u. per kw-hr. output on the feeders for 1930 (the first full year's operation) was 12,874. For 1931 this was 12,050. The average for the first six months of this year is 11,795. The economy at Deepwater is exceptionally high for a plant employing a straight thermal cycle, but the most interesting part is that it has been obtained at a very low cost in investment per kw. Deepwater is a definite proof of the point made before that economy in operating cost and low investment cost are not necessarily contradictory and that their combination is perfectly feasible. It can not be done however by adhering to obsolete practise and by putting a double guard on each safety and protective feature.

A. H. Sweetnam: Loop service to high-tension customer substations is quite generally supplied except where the customer has generating capacity sufficient to carry his load. In such cases a tap from a transmission line is carried into the station.

Transformer ratings are figured on the basis of approximately 0 deg. C. ambient during the winter peak and 25 deg. C. during summer peak.

I. E. Moultrop: In some of these papers the statement is made that construction projects have been carried out in advance

of load requirements for reasons of reliability or economy in operation.

We have undertaken construction work in advance of load requirements for reasons of reliability, but it has been confined mainly to the replacement of obsolete and inadequate equipment. We have not in general committed the Company to investments in advance of load requirements for reasons of economy in operation, feeling that the expected returns from such investments are not always fully reflected in the Company's balance sheet. The exception to this, however, is in the case of such items as converting attended substations to the automatic type where definite labor savings can be predicted and are inevitable.

Reference is made in one or two of the papers to the question of tie-line losses. We believe it to be fundamentally necessary, in order to arrive at accurate results in allocating loads to various sources of generation so as to obtain the largest overall economy, to take into consideration the incremental tie-line losses. This applies particularly in the case of interchange contracts. Ampere square meters for adjusting these losses at metering point are available and provide a simple means of correction for losses.

L. L. Perry: Conclusion 2 in the paper on the Chicago District applies to increase in capacity and not to replacement in existing capacity. Up to the present depression most metropolitan districts have had almost yearly to make increase in generating capacity in order to maintain adequate reserve. The less efficient equipment held in reserve, since it seldom runs more than a few hours per year, is usually much cheaper for reserve when fixed charges are included.

Electrical Equipment for Precipitation Service

BY H. SPEIGHT[1] and V. G. RYDBERG[2]

Member, A.I.E.E. Non-member

THE application of a strong electrostatic field accompanied by corona discharge to the cleaning of gases was first shown by Hohlfeld in 1824. His observations were extended by Sir Oliver Lodge in 1884 who continued the work and made a practical installation at a lead smelter in Scotland.

Later, this work was extended by Dr. Cottrell in 1905-6, leading to the development of the electrical precipitation process for the separation of solids and liquids from gases.

FIG. 1—INSTALLATION IN NON-FERROUS FIELD

It was found that if the central or smaller electrode in a precipitator is made negative, corona can be obtained at a much lower voltage. Electrons in this field acquire such velocities they break up the gas molecules into positive ions and additional electrons. This augmented supply of electrons moves toward the outer or positive electrode and they are trapped by the solid particles which thereby obtain a negative charge. The charged particles are attracted to the positive pole and impinge upon it with considerable force. Here they release the trapped electrons and cling to the electrode surface by adhesion.

The early applications were cleaning of sulfuric acid mist and the cleaning of sulfur gases in the non-ferrous field to recover the non-ferrous metal particles which were being carried away in the discharge gases from the copper smelters. Later the field of application extended to cement, acid fumes, high temperature gas cleaning, detarring of combustible gases, removal of organic materials and miscellaneous applications.

For the best results in precipitation, uni-directional current is used, and a further fundamental condition is that the discharge electrode must be negative and the collecting electrode positive.

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The extension of the field of application requires varying characteristics of power supply to the corona field. The electrical equipment usually consists of transformer (specially designed for this service), mechanical rectifier, motor-generator, rectifier motor, switchboard, and accessories. This apparatus is all specially designed to withstand the unusual and difficult conditions of the precipitation circuit, having been generally successful over a period of years. Fig. 1 illustrates an installation of electrical equipment for precipitation service in the non-ferrous field.

The electrodes for corona discharge consist of fine wires or rods hanging in the precipitator, the collecting electrodes are plates or pipes. The potentials used are between 20,000 and 75,000 volts, the actual voltage depending upon the design of the precipitator and the material to be treated. A rectifier connected to the high-voltage side of a step-up transformer is used to obtain the high-potential uni-directional voltage. In one form of the mechanical rectifier the stator consists of four segments or shoes spaced 90 deg. apart on a circle and mounted on fixed insulated arms. The rotor which is driven by a small induction motor designed to operate at synchronous speed consists of two insulated arms displaced 90 deg., on the ends of which the contact tips are mounted and connected in series.

There are many disadvantages to the mechanical rectifiers which may be summarized as follows:

1. The continuous spark discharges cause oscillating discharge and surges which create additional stresses on the transformer insulation.
2. The wave form is very irregular. Fig. 2 illustrates this.

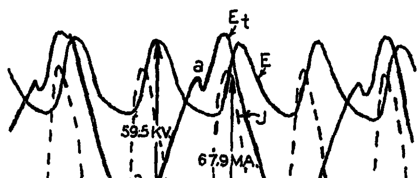

FIG. 2—WAVE FORM OF VOLTAGE MECHANICAL RECTIFIER

3. The contact tips and shoes commence wearing when the rectifier goes into service, continually decreasing the actual voltage at the precipitator. In addition a considerable amount of fixed resistance is necessary to assist in absorbing the energy of the surges caused by the spark discharge.
4. Equipment for suppression of radio interference is necessary.
5. Manual or automatic polarity control must be furnished, adding to the complexity of the control equipment.
6. It is noisy in operation.

The expansion of the precipitation field has created a growing demand for a rectifier unit that will furnish a more even wave shape and maintain the same precipitator voltage over an extended period of time. With the improvement in the radio art, and the increasing use of rectifiers in power applications, the obvious alternative is tube rectification. By this method relatively smooth wave form of uni-directional current is obtained as illustrated in Fig. 3.

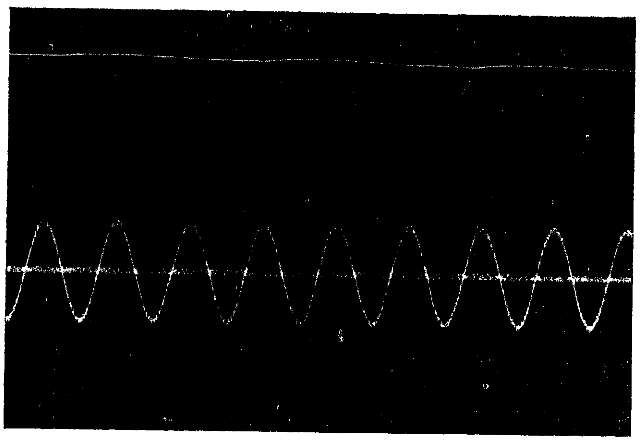

FIG. 3—WAVE FORM OF VOLTAGE TUBE RECTIFIER

The scientific study of the electrostatic field and corona discharge will be greatly assisted by tube rectification, which will permit assembling of data of the variables existing in precipitation applications, due to varying temperatures, conducting and non-conducting properties of the materials being treated.

In many applications the precipitator receives gases containing varying percentages of conducting and non-conducting particles. To meet these varying conditions, we should maintain constant current, which will necessitate raising or lowering the voltage, utilizing to the maximum efficiency the fixed spacing of the electrodes in the precipitator.

The load of the precipitator is very unusual and unique to this application. A negative lead from the rectifier connected to the wire electrodes in the precipitator is shown diagrammatically in Fig. 4. The corona discharge from the negative wire electrode ionizes the gases, thus reducing the normal dielectric insulation, thereby permitting the conveyance of the electron, by the particle, and increasing the normal capacity of the circuit.

The tube type rectifier furnishing uni-directional supply, to this unusual load will have the following advantages:

1. Less space.
2. No surges in the circuit due to rectification.
3. The wave form supplied will be regular.
4. The voltage will remain constant.
5. No radio interference from the rectifying equipment.
6. Polarity is automatically controlled.
7. Operation is very quiet.

The complete equipment for this application consists of transformer (including filament heating), tube rectifier, control, induction voltage regulator or tap changer, and sectionalizing switch for each compartment of the precipitator.

Due to the inherent characteristics of the precipitator the transformers must withstand heavy surges or transient stresses. If special arrangement were not made to avoid this condition these surges started by the flashover of the precipitator would occasion concentrated voltage stresses in the coils adjacent to the line terminal.

The severity of the transient is decreased by a series resistor between the tube and the precipitator, this reduces the voltage crest.

The concentration of voltage stress across the coils at the line end of the transformer windings is also prevented by increasing the effective capacitance between adjacent coils and largely eliminating the capacitance between these coils and the core and low-voltage windings. This is accomplished by designing the transformer so that the coils are located in a relatively uniform dielectric field or by increasing the electrostatic coupling between the coils, and a metallic plate interposed between these coils and the core.

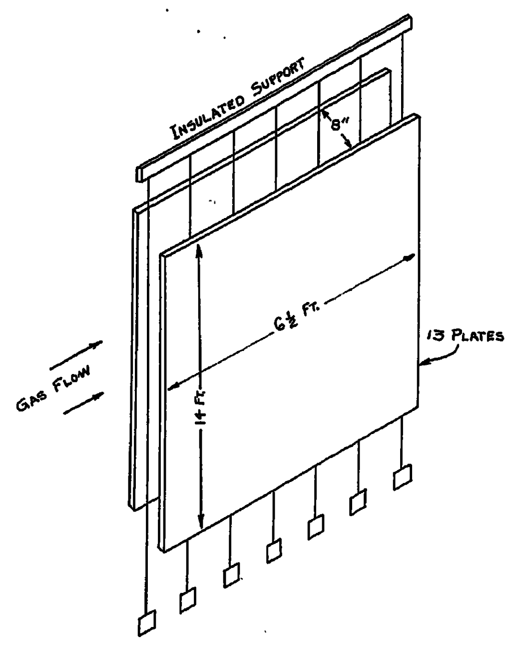

FIG. 4—DIAGRAMMATIC SKETCH OF PLATE TYPE PRECIPITATOR

For several years it was considered the best engineering practise to place a choke coil in series with the transformers, to choke or damp out any high frequency set up by surges in the circuit. Recently it was proved by laboratory tests and measurements that conditions may exist where the choke is the cause of a very high surge voltage being impressed across the transformer coils. It has also been proved that a choke coil shunted by a resistor gives a much greater damping effect than

is obtained when using a plain choke coil. However, if both of these are replaced by a series resistance the best damping effect is obtained, and the smallest surges are impressed across the high-voltage terminals of the transformer. Therefore we see that the best protection is obtained by a shielded transformer and a series resistance between the rectifier and the precipitator.

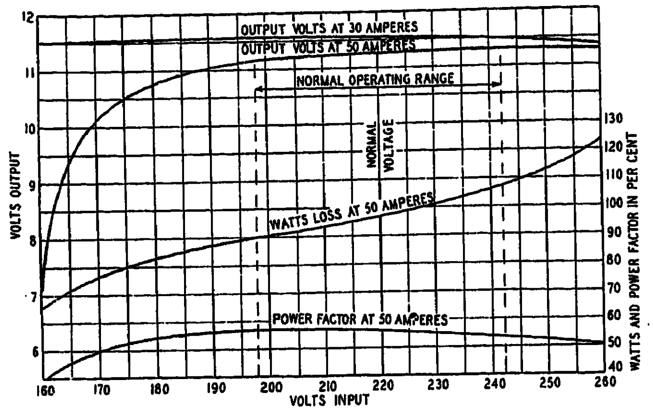

FIG. 5—CHARACTERISTIC CURVE OF STATIC VOLTAGE REGULATOR

The power supply for tube type rectification must furnish constant voltage for heating the filament. This constant voltage is usually supplied by a small induction regulator or a specially designed static voltage regulator which holds the filament voltage very constant. See Fig. 5.

It is necessary to vary the value of the uni-directional voltage supply depending on the type of precipitator, type of material being treated, and the load carried. As previously mentioned, this variation in voltage of about 50 to 100 per cent has been obtained by taps in the primary winding of the main transformer. There are two methods used for changing the taps bringing all taps to a special knife switch on the switchboard, or using a tap changer under load. The precipitator voltage may also be varied by the use of an induction regulator in the power supply line.

Fig. 6 illustrates core and coils and filament transformers of a tube-rectifier precipitation unit.

The rectifier tube for this service must be of sturdy construction to give sufficient length of life to make the application of tube rectifier unit commercially practical. Fig. 7 illustrates the construction of a high-voltage tube and Figs. 8 and 9 show the plate and filament characteristics. This tube is rated 750 milliamperes maximum peak current, 150 kv. maximum inverse potential.

The thermionic rectifier depends for operation upon the fact that when two electrodes (one which is heated) are placed in a high vacuum, current flows through the space between them, (when the heated electrode is negative). This is because the current is the electron stream emitted from the hot filament.

The peak plate current of a tube is limited by the electron emission from the filament or cathode. The emission in turn is dependent upon the cathode temperature and area. It is possible to operate the filament at less than rated voltage if the peak plate current drawn from the tube is sufficiently reduced. The lower filament temperature will result in slower evaporation of the filament material and consequently longer life.

If the filament voltage is reduced below that which is necessary to supply the peak plate current, the voltage drop between the filament and plate will increase. This will cause excessive heating of the plate and may result in damage to the tube.

The rated maximum crest inverse plate potential is the highest voltage that may safely be applied to the tube in the direction opposite the one in which the tube is designed to pass current. It is a measure of the insulation of the tube when the plate is at a negative potential. In addition to being limited by the distance between anode and cathode this rating is determined by

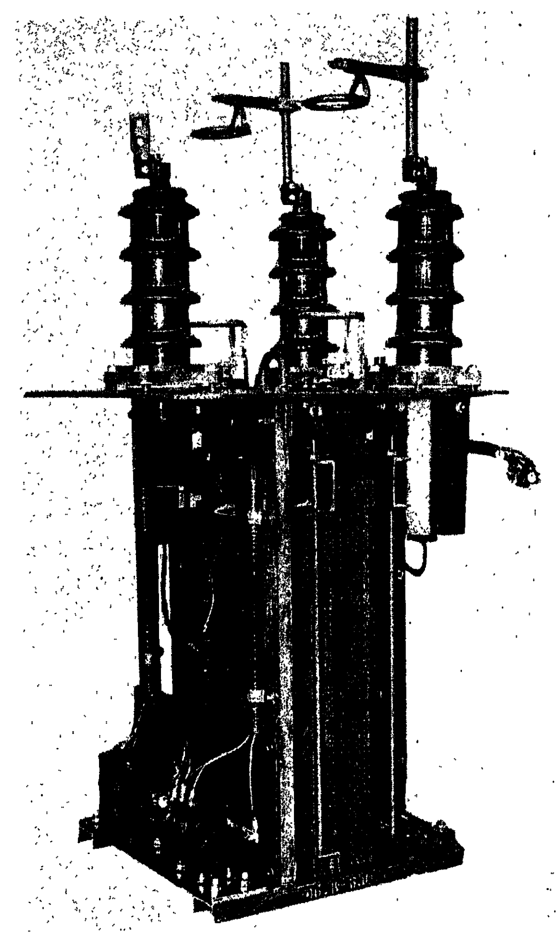

FIG. 6—TRANSFORMER FOR TUBE RECTIFICATION

the size and shape of the anode and its position with respect to the cathode. The anode or plate must be large enough to radiate the heat properly due to power losses in the tube. If it is heated too high in temperature there is a possibility of electrons emitting from it, causing an arc back from the cathode to the anode with consequent damage to the cathode. Hence the

important constants of the tube are (a) filament voltage and current, (b) the peak voltage permissible between electrodes, (3) the peak plate current output.

The constancy of filament voltage and current will affect tube life. The emission increases with the temperature, a 2½ per cent increase in the terminal voltage being sufficient to double the evaporation of the filament material, thus the necessity of maintaining a constant filament voltage is emphasized.

The second constant of the rating to be considered is the maximum peak voltage meaning the highest peak voltage the rectifier tube can safely stand, in the direction opposite to the current flow. The value of the inverse potential will depend upon the voltage of the supply circuit and the type of circuit used for rectification.

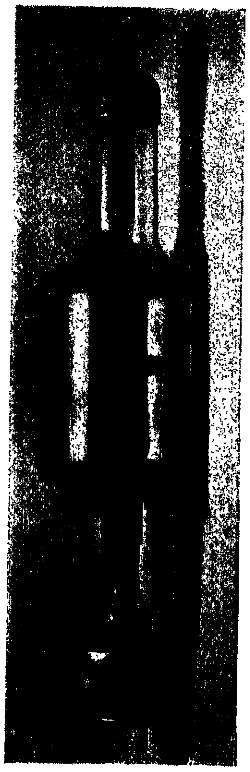

Fig. 7—High-Voltage Tube—150,000 Volts Maximum, 750 Milliamperes Maximum

The circuits most frequently employed are:

1. Single phase, full wave, employing two tubes. See Fig. 10.

2. Single-phase, full-wave circuit in which four tubes are used.

3. Three-phase, half-wave circuit requiring three tubes.

The theoretical maximum voltage which can be supplied in a single-phase circuit is 1.4 × r.m.s. value. However, the inverse potential may exceed this value. In the type of circuit under consideration, where capacity is coupled with a high insulation resistance, the circuit is charged to maximum potential of $1.4 \times E$ during the conducting period. When the tube is passing current this charge may not leak with sufficient rapidity so that a value nearly equal to $2 \times 1.4\ E$ may be obtained across the tube on the inverse half-cycle. Such things must be kept in mind when selecting a tube with the proper peak inverse potential rating for the application.

When using single-phase full-wave circuit with two tubes, (Fig. 11), when the right hand tube is conducting current, the drop across it is comparatively low, hence the effective voltage across the other tube will be $2E$,

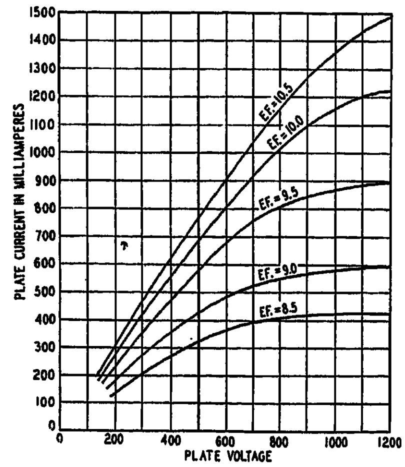

Fig. 8—Plate Characteristics of Tube Illustrated by Fig. 7

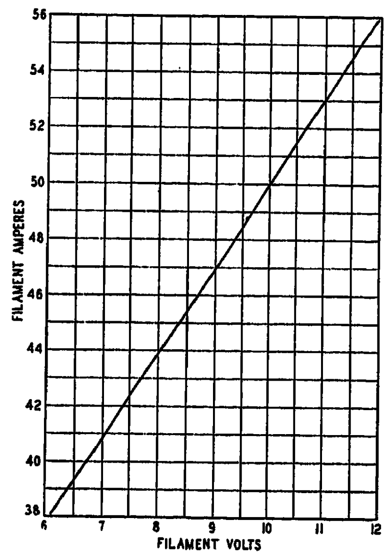

Fig. 9—Filament Characteristics of Tube Illustrated by Fig. 7

where E is the r.m.s. value obtained from one-half the transformer winding. The maximum peak voltage will therefore be 2×1.4 or 2.8 r.m.s. voltage from each half of the transformer.

The input capacity of the transformer for single-phase full-wave rectification is 1.1 × the kilowatt output on the d-c. side, thus where the d-c. side is 10 kw. the transformer would be 11 kva. on the primary side since this is the measurable input.

A number of installations of tube rectification has been made utilizing various combinations of transformer connection and number of tubes. The description of one installation will be cited as an example.

Fig. 11 illustrates an installation of commercial type vacuum rectifier. Note the compactness of the unit assembly giving complete control of the apparatus with wide voltage range which is necessary for the application. Added to the relays and meters needed in the control scheme, there is mounted on this panel a contactor for the filament supply circuit and a similar contactor for the main supply to the primary of the transformer. A single handwheel controls both the tap changing equipment and the usual series resistance in the primary of the transformer. This arrangement gives a smooth voltage variation of approximately 50 per cent range on the high-voltage side.

The single-phase full-wave scheme of rectification is used, consisting of a tube between each end of the transformer winding and the grounded positive side of the precipitator. The center of the main winding is tapped for the negative high-tension lead to the precipitator circuit.

The control scheme is relatively simple and is self-protective. The main feature is interlocking to insure the filaments are energized a few seconds before the plate of the tube. This prevents flashover which might result, because the full voltage applied is effective in speeding up the electrons before the filament has reached normal temperature. This bombardment results in overheating of the plate. In addition to this interlocking feature the only protection necessary is against short circuits, overloads, and loss of filament.

Fig. 10 illustrates the control scheme. Closing of the knife switch energizes a time-delay relay which will complete the circuit for plate supply contactor designated 4. A relay with coil in the primary of the filament transformer must first be energized otherwise contactor 4 could not be energized. When contactor 4 closes, primary of the transformer is energized and voltage applied to the tube depending upon the setting of the tap changer. Rectification continues until the circuit is disconnected by the pushbutton or operation of protective relays. Relays to protect the tube from damage due to overload or short circuit will be connected in the control and will function in the usual manner. A frequent

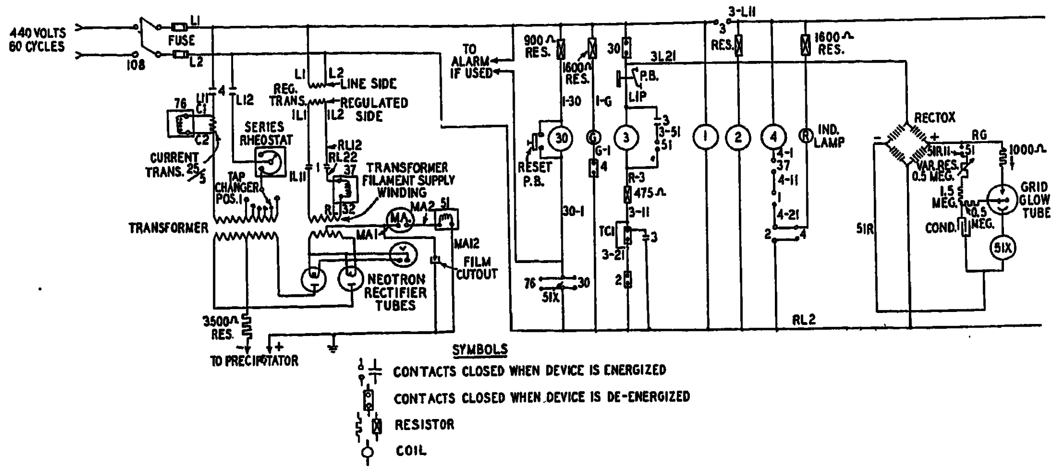

Fig. 10—Control Scheme for Equipment Illustrated in Fig. 11

Item	Description	Item	Description
1	Filament supply contactor (2 pole)	51	H.T. D.C. (0.5 to 1.5A) short-circuit protection relay
2	Plate supply timing relay	51X	Aux. relay for 51
3	Master relay	76	Primary overcurrent relay (4-12 amperes)
4	Plate supply contactor (2 pole)	G	Green lamp—indicates "off"
108	Control power switch 2 P.S.T.	R	Red lamp—indicates "on"
30	Lockout relay (1*M*, 1*B*) 440-volt coil	TC1	Interlock on tap changer, closed when on No. 1 position. (Not used)
37	Filament undercurrent relay 2-6 amperes		

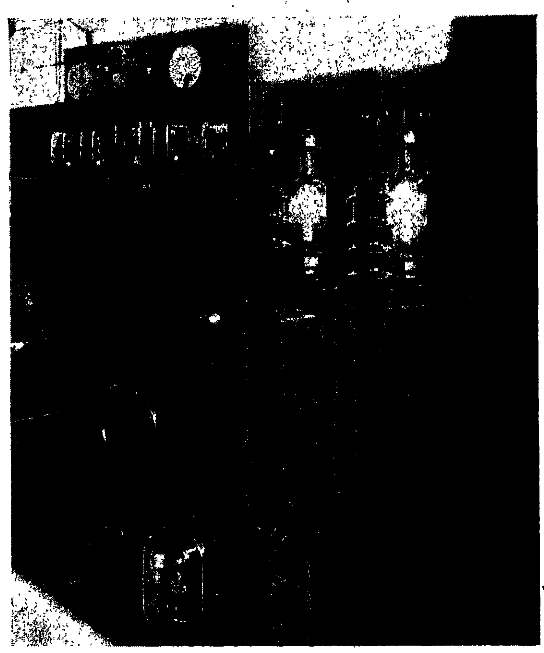

Fig. 11—Illustrates a Typical Installation of Tube Rectifier

cause of short circuit and overload is charged to the character of the gas. The acid content of the gas, gas temperature, changes in dust or fume content, have a marked effect on the dielectric characteristics of the materials resulting in a change in load. Since the equipment should require no attendant it is not desirable to take it out of service whenever any momentary overload occurs. Therefore if the circuit is made to reclose automatically a certain number of times, protection is obtained for the tube, if the short circuit is only a momentary condition the equipment is permitted to continue in operation.

This protection is obtained on the installation by means of grid-glow auxiliary relays which consist of a value to energize the auxiliary relay 51-*X* when the equipment is automatically locked out.

The tube rectifier installation permits consideration of the possibility of an automatic control of the precipitator unit. A proposed scheme is shown in schematic diagram, Fig. 12. This regulating equipment would consist of a constant-current regulating device, responding to the changes in the primary current of the transformer. These changes are caused by changes in the condition of the gas supplied to the precipitator, the object of the automatic regulator being to maintain current of a pre-determined amount, calculated as the most efficient operating value. To accomplish this, the voltage applied to the precipitator must be controlled

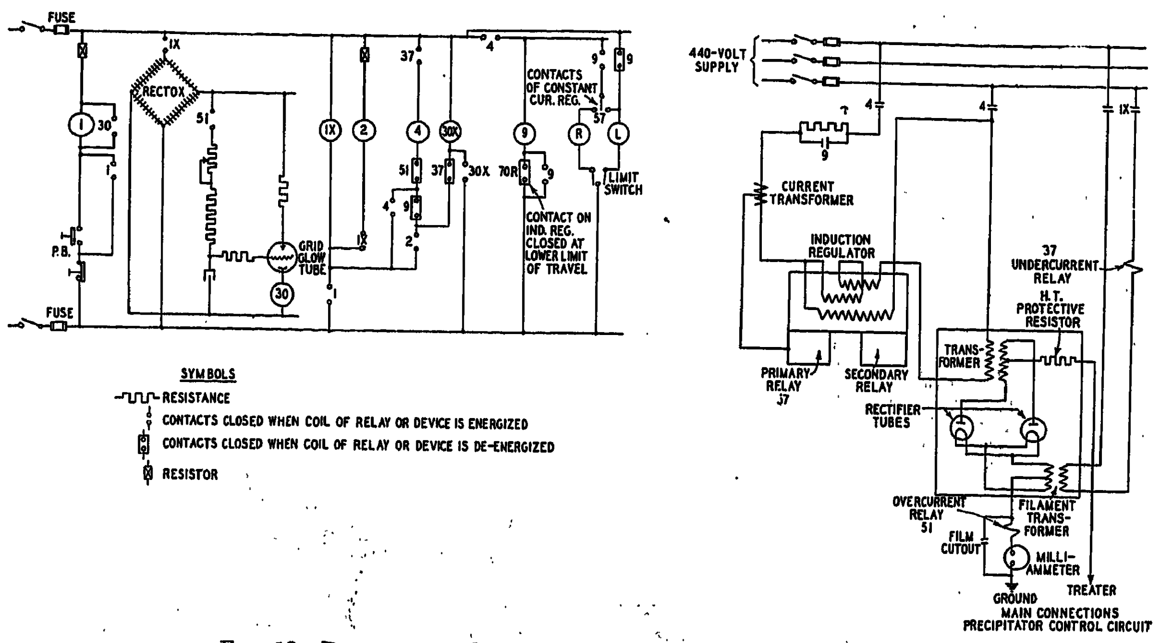

Fig. 12—Diagram of Control for Full Automatic Equipment

LEGEND

Item	Description	Item	Description
1	Master relay	37	Undercurrent relay
1X	Filament supply contactor	51	Overload relay
2	Timing relay	57	Constant current regulator (primary relay)
4	Main contactor	R	"Raise" coil of secondary relay
9	Control contactor	L	"Lower" coil of secondary relay
30	Lockout relay	70R	Interlock on induction regulator, closed at lower limit of travel
30X	Auxiliary lockout relay (hand reset)		

cold cathode grid-glow tube, a small condenser, associated resistors and an auxiliary relay designated as 51-*X*. The grid-glow tube breaks down or discharges only at a predetermined voltage across the condenser. The over-current relay being instantaneous, will immediately close its contacts in case of short circuits, one set of contacts in the grid circuit of the grid-glow relay energizes the condenser circuit putting a certain potential on the condenser. This charge is not sufficient to cause discharge of the grid-glow relay but does not leak off for some time. After a short period the plate supply contactor is closed and if the short circuit is repeated the charge on the condenser is increased. The periodic opening and closing continues until the charge on the condenser reaches a sufficient

by a suitable regulating device. This device raises or lowers the voltage to keep the current constant.

The primary relay as controlled by the current of the circuit will control the induction regulator, thereby raising or lowering the voltage as required. The voltage regulation by this arrangement is smooth and gives quick response, thereby maintaining a constant current to the precipitator regardless of the changes in the characteristics of the gases.

Tube installations have given an operating life of over 4,000 hours for the tube. This is a satisfactory commercial life, and in addition to the advantages described above, the vital fact, judging by experience of installations to date, is a higher recovery per kilowatt input obtained than with mechanical rectification.

Discussion

W. C. Kalb: As a supplementary consideration to this valuable paper it may be of interest to consider developments of recent years relating to the adaptation of carbon tubes to electrostatic precipitation units operating on highly corrosive fumes, such as sulfuric, hydrofluoric, and phosphoric acids.

From a chemical standpoint, carbon is very inert in the presence of all reagents except those of high oxidizing power. It is attacked by free oxygen only at temperatures exceeding 600 deg. F. It possesses high electrical conductivity and mechanical strength and does not soften or melt under the influence of heat.

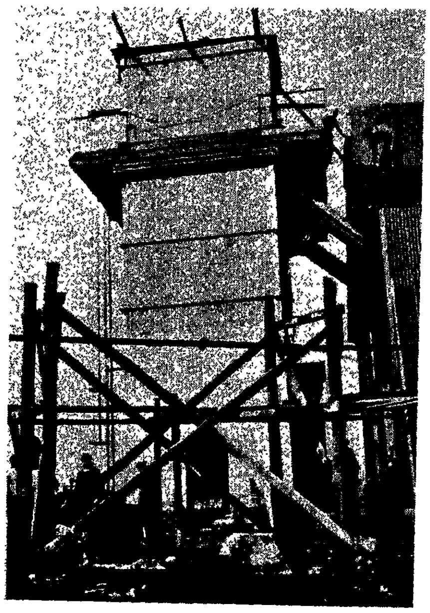

FIG. 1—AN EXTERNAL VIEW OF AN ELECTROSTATIC PRECIPITATOR EQUIPPED WITH CARBON TUBES

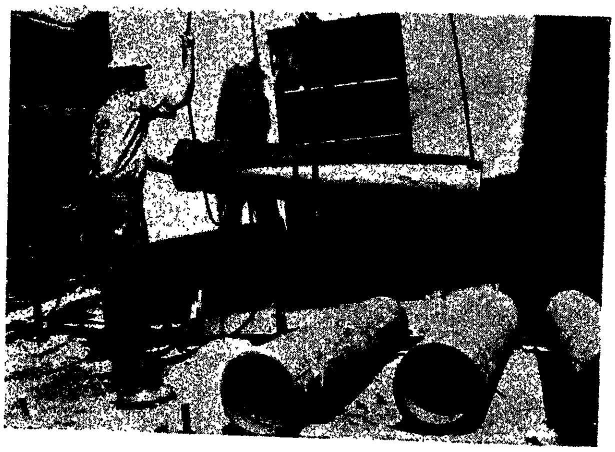

FIG. 2—CARBON TUBES

These characteristics overcome many of the difficulties that have been experienced with other tube materials used for the precipitation of corrosive fumes or acid mist.

Carbon tubes are now extensively used in the precipitation of phosphoric acid in the presence of hydrofluoric acid. They are also used for the collection of strong, hot acid mist in the manufacture of sulfuric acid by the contact process and in the concentration of sulfuric acid in drum type concentrators where the diluted acid is violently agitated by a blast of air at temperatures as high as 1,200 deg. F.

Carbon tubes lend themselves readily to the requirements of precipitator construction for chambers of either circular or square cross section. Two sizes are commonly used; the one 9¾ in. outside diam by 7¾ in. inside diam and the other 13 in. outside diam by 10 in. inside diam. These tubes are usually supplied to the customer in 6-ft. lengths which can be joined together by lap or threaded joints.

The precipitator equipped with carbon tubes shown in Fig. 1 is of rectangular cross section. The carbon tubes themselves are illustrated in Fig. 2. It will be observed that the ends of the tubes are threaded with male and female threads, and that one end of the tube supported by the hoist is recessed for the carbon blocks, which support it in the precipitation chamber. In precipitators of square cross section, the brick arch construction shown in Fig. 3 is commonly used for support of the precipitator tubes. Fig. 4 illustrates the method of supporting the tubes by means of carbon blocks carried on these brick arches. Fig. 5 shows the completed assembly viewed from the upper portion of the chamber.

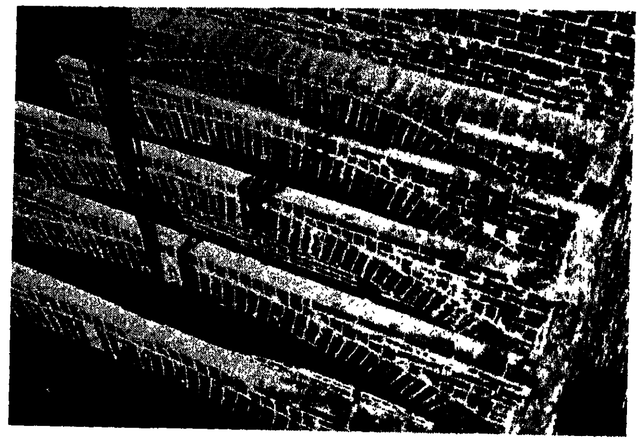

FIG. 3—BRICK ARCH CONSTRUCTION

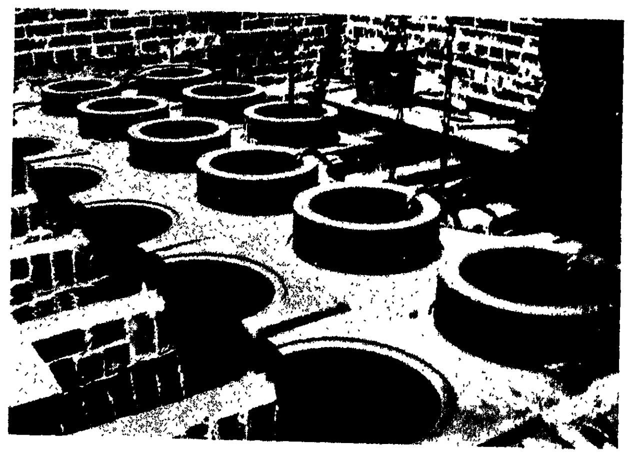

FIG. 4—BRICK ARCHES CARRYING CARBON BLOCKS FOR SUPPORTING THE TUBES

Inasmuch as the brick arch construction is not well adapted to precipitator chambers of circular section, lead covered "I" beams are used as supporting members for the tubes in this type of chamber. Except for this detail, the method of construction is practically the same as in chambers of rectangular cross section. In addition to carbon being used for tubes, carbon blocks are also used as a construction material for anchoring the bottom of the tubes and the lower end of the negative electrode wires.

Carbon tubes have now been used in precipitation service for several years and have conclusively demonstrated that they are cheaper, lighter, and more permanent than acid resistant metal tubes. They are more easily cleaned than lead tubes, do not get out of shape, and will not pit or locally fuse should arcing occur. The high electrical conductivity of carbon gives it a marked advantage over ceramic tubing which is dependent for its electrical conductivity upon a film of acid on its inside surface.

V. G. Rydberg: The design of high-voltage rectifier tubes for precipitation service has been aided by the experience obtained in rectifier tube applications for other fields of activity, such as radio and xray. In radio use the peak inverse voltage requirements of rectifier tubes is comparatively low, being about 50,000 volts maximum. The plate current, however, in the larger vacuum types is quite heavy, being of the order of several amperes, and in the mercury vapor type several times this much.

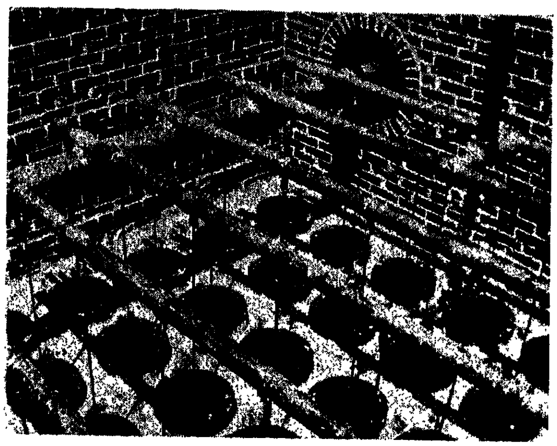

FIG. 5—COMPLETE ASSEMBLY VIEWED FROM ABOVE

In such tubes the problem of insulating against the working voltages does not offer particularly serious difficulties. In the vacuum type rectifiers it is a problem, however, to cool the plate because of the heavy plate current and comparatively high tube voltage drop. In some tubes it is necessary to resort to water cooling to take care of the heat dissipation. In the mercury vapor type, however, the plate dissipation is low because of the low tube voltage drop.

Rectifier tubes used in xray work are designed for a very different type of service. In this application it is necessary to supply direct current at very high voltages while the plate current requirements are comparatively low. Tubes which withstand a peak inverse voltage of 250 kv. may not have to pass more than 100 milliamperes peak current, and are usually in service for very short periods of time at just a very few milliamperes average current.

Tubes for precipitation service, particularly the heavy duty types, must be designed for high peak inverse voltages and also relatively high peak plate currents which are applied continuously twenty-four hours of the day. This means that the plate must be sufficiently large to dissipate the heat losses in it and must also be spaced relative to the cathode and of such conformation as to prevent flash backs due to improper distribution of the electric field within the tube.

The arcing arm or distance between the cathode and anode terminals must also be sufficient to prevent flashover outside the tube. In this connection it is desirable to clean the bulbs periodically in service to remove accumulated deposits of conducting material.

In the WL-612 tube shown, it is noted the plate has curved edges to distribute properly the electric field and prevent concentration at the edges. A shield around the cathode serves partially to concentrate the electron stream and prevent bombardment of the bulb. There is also a shield extending down from this cathode shield over the cathode stem to prevent electrical puncture of the press. A shield over the anode press serves the same purpose for the seal at the other end.

Due to the heavy filament used in this tube to give long life and to provide the peak plate current, it is necessary to use auxiliary filament leads as the standard socket will not handle reliably the 50 amperes of filament current at 10 volts. If high resistance were introduced into the filament circuit so as to cut down the current appreciably, there would not be sufficient emission, and the plate voltage drop would go up with consequent damage to the tube. This contingency is eliminated by the use of these flexible leads.

These points of design provide a line of tubes to cover a wide range of applications in the precipitation field with assurance of steady performance and long life.

H. Speight: Mr. W. C. Kalb has supplemented the paper with very valuable information on the benefits on carbon tube applications for precipitator units operating in corrosive atmospheres.

A large number of applications has been made in the chemical field where the corrosive conditions fully justify the use of carbon tubes or plates and in recent years installations in combined metallurgical and chemical plants have resulted in the electrodes of precipitator units being corroded away within six months.

We believe the carbon tube applications described by Mr. Kalb for the chemical field might be advantageously used in other fields.

Mr. V. G. Rydberg has given some valuable data regarding the design of the tube for the severe precipitation service which design features have a bearing on the successful application of tubes in this field.

We believe that the improved wave form from tube rectification and closer control will result in higher operating efficiencies in precipitation service.

Oxide Coatings on Aluminum

BY J. D. EDWARDS, Non-member; MARTIN TOSTERUD, Non-member; and H. K. WORK, Non-member

THE interest in oxide coatings on aluminum began with the discovery of the metal about 100 years ago, for the chemical attraction of aluminum for oxygen is one of the most important characteristics of the metal. At various times in the history of aluminum, attention has been focused on the oxide film, from the scientific standpoint or from the commercial standpoint. To the scientist, for example, the electrical characteristics of the oxide film have been of great theoretical interest and for many years have been the subject of experimental study and speculation. Important commercial use of the film in various electrical devices has followed upon the scientific studies.

Aluminum owes its stability and resistance to corrosion to the invisible oxide film always present. Aluminum, whenever exposed to air containing moisture, immediately becomes coated with a film of oxide; this film is ordinarily invisible and not more than a relatively few wavelengths of light in thickness. Ordinarily the film is quite impermeable, so that pure aluminum will stand exposure to water with little corrosive action. The presence of this oxide film is quite apparent when one attempts to amalgamate aluminum. Aluminum and mercury combine readily, but when covered by an oxide film the mercury will not wet and hence will not combine with the aluminum. Even if the aluminum is freshly abraded, as by filing, scratching and the like, and then plunged into mercury, no action takes place because the oxide film reforms instantly. If, however, the oxide film is removed by abrasion while immersed in the mercury and out of contact with air, amalgamation takes place.

A very important characteristic of this oxide film is its impermeability. The oxide formed from aluminum occupies a greater volume than the aluminum from which it is formed. This apparently results in a compact and non-porous film with high protective properties. Even on continued heating at high temperatures, the oxide film shows relatively little increase in thickness. Although impermeable to gases, the oxide film as naturally formed has a negligible electrical insulating effect and offers little resistance to the passage of current, even at very low voltages. This is fortunate, and permits the manufacture, for example, of variable air condensers with aluminum plates held in their mountings by mechanical pressure, with no increase in resistance over similar condensers of other metals in which the plates are soldered to the supporting pillars.

The asymmetric character of the film "artificially" produced, when aluminum is made anode in various electrolytes, has been of great scientific and considerable commercial interest. Since the rise of the radio industry, extensive use of film-coated aluminum has been made in the electrolytic rectifier and, more recently, in the electrolytic condenser. High capacity in small volume and at low cost has proved a great stimulus to the development of the electrolytic condenser. Originally marketed in the form of a cell containing electrodes immersed in a substantial volume of electrolyte, the trend for small condensers, at least, is now largely towards the so-called "dry" form, in which a limited volume of electrolyte is held absorbed in a paste kept in contact with the electrodes. In all of these devices, however, the oxide film—at least the active part—is quite thin.

The extensive use of oxide coatings having thicknesses comparable with those of paint films is a relatively recent development. If aluminum is made the anode in boric acid, the potential drop at the anode may be increased to a value of about 400 to 600 volts with very little current passing; the film, once formed, is thin and shows little tendency to decrease or increase in thickness. If, however, an electrolyte of different chemical characteristics is chosen, as for example, a dilute solution of sulfuric or oxalic acid, a characteristically different behavior is noted. Within limits, the oxide film may be built up to a substantial thickness, since the potential may not rise above 10 to 50 volts, and current continues to pass until thick films have been formed, say 0.001 in. or over. Films formed in this latter way, when removed from the electrolyte and dried, have desirable mechanical, chemical, and electrical properties. The film in respect to hardness partakes of the characteristics of corundum, which is a hard, crystalline oxide, Al_2O_3. Because of this hardness, it possesses wear and abrasion-resistant qualities which can be made use of commercially. The dielectric strength of these dry films can be made sufficiently high so that they can be used for purposes of electrical insulation on wire, sheet and foil, for conductors and condensers. In a chemical way, the films can be made with or without high adsorptive properties, so that they can be colored by absorption of dyes or mineral pigments, thus opening up a new and extensive field for the obtaining of decorative effects. These thick oxide films on aluminum can be obtained not only by electrolytic treatment, but also by direct chemical action of various solutions on aluminum. The properties of these thick oxide films will be discussed in succeeding paragraphs.

In the formation of oxide coatings on aluminum by the electrolytic action of current, the oxide formed is produced at the interface between the aluminum and any oxide coat already existing on it. It might be thought, therefore, that the oxide coat could be in-

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creased to any thickness as long as the coating remains sufficiently permeable to permit the passage of current. There is another limiting factor, however, and that is the solvent action of the electrolyte upon the oxide film. Most of the electrolytes which are useful for producing thick oxide coatings have an appreciable solvent capacity for aluminum oxide, usually increasing with rise in temperature, and the anodic coating process becomes a race between the oxidizing action of the current and the solvent action of the electrolyte. The oxide coating may also have its characteristics changed by specific chemical reactions with the electrolyte.

An interesting experiment with an electrolyte of low solvent action gave a series of eight coatings which were determined by direct measurement of microscopic sections to have an average thickness of 0.00038 in. Direct measurement also showed that the sheet had increased in thickness by 0.0002 in. as a result of oxidation on both sides, so that the increase in thickness attributable to a single oxide film is 0.0001 in. The aluminum, therefore, in forming aluminum oxide, increased in volume by about 35 per cent. This is a difficult measurement to make with precision, and values were obtained for the percentage increase in volume by oxidation, which ran from about 15 to 60 per cent. When, however, electrolysis was carried out with a solution of high solvent power for aluminum oxide, the sheet frequently showed a total decrease in thickness many times the thickness of the oxide coating, even though the coating itself was of substantial thickness.

The coatings described in the previous paragraph were subjected to x-ray examination by the powder method and were found to be amorphous—at least no evidence of crystallinity was observed. The water in the coating is therefore probably held by adsorption, and not as one of the crystalline hydrates of aluminum. However, by a special after-treatment the oxide can be converted, at least in part, into crystalline aluminum mono-hydrate. The change is accompanied by a marked decrease in the permeability of the film and an increase in its dielectric and protective properties.

From the standpoint of the electrical engineer, the possibility of using an oxide coat as insulation on aluminum conductors is a matter of considerable interest. The idea, of course, is quite old and some commercial use has been practised, particularly abroad. The present advanced technique and knowledge of oxide coatings now available has created a new interest in these coatings. With certain types of electrical machinery, the use of aluminum conductors would be advantageous from the standpoint of the weight reduction possible. Another advantage of the oxide-coat-insulation is the fact that it is non-combustible and will stand fairly high temperatures without deterioration. There is even a possibility of its use as a dielectric in dry condensers. The break-down voltage of oxide films is roughly proportional to the thickness of the film. The break-down characteristics, however, are also dependent upon the specific physical and chemical characteristics of the film. In Fig. 1 is shown a series of observations on the breakdown voltage of oxide films on commercially pure aluminum, plotted as a function of the thickness of the oxide film. This particular film was made by anodic coating of aluminum in a 15 per cent solution of sulfuric acid held at a temperature of 75 deg. fahr. To produce an oxide film one mil in thickness required, under the operating conditions, a period of about one hour. By special after-treatment, without introducing any organic material into the film, such as that referred to in a pre-

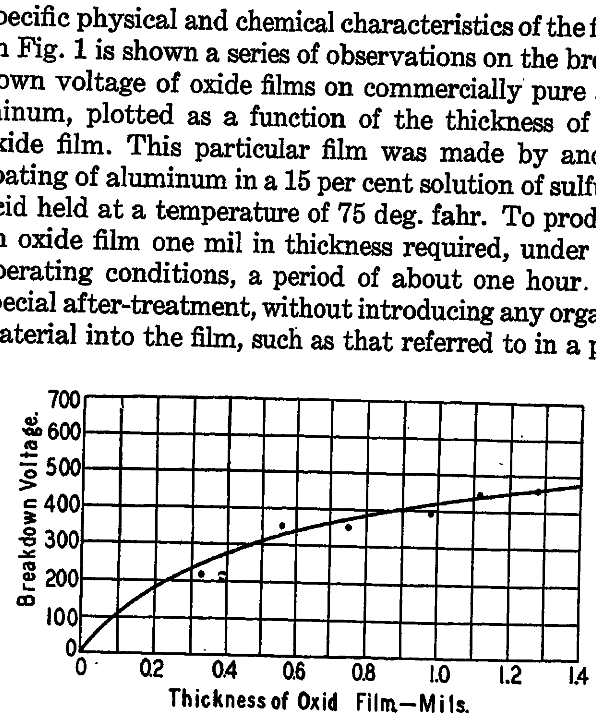

FIG. 1—BREAKDOWN VOLTAGE OF OXIDE FILMS ON COMMERCIALLY PURE ALUMINUM

vious paragraph, the break-down voltage of the film may be increased as much as 50 per cent or more. The oxide coatings can also be produced in very absorbent form, and in this condition can be impregnated with oils, waxes, enamels, etc., with a substantial increase in insulating value.

That the oxide coat is very much harder than the base metal is at once obvious if an attempt is made to scratch the surface. Some quantitative figures have been obtained by subjecting oxide films of various thicknesses to an abrasion test which consists of abrading the surface with an aloxite wheel under light pressure. The abrasion resistance is measured in terms of the number of revolutions which the specimen makes against the abrasive wheel. These figures are given in the following table.

ABRASION RESISTANCE OF OXIDE COATINGS AS A FUNCTION OF THICKNESS

Thickness of coating Inches	Abrasion resistance—revolutions against Aloxite Wheel
0.00011	15 revolutions
0.00019	95 revolutions
0.00031	268 revolutions
0.00037	365 revolutions
0.00074	2,563 revolutions
0.00148	7,061 revolutions

According to these figures, the abrasion resistance of the oxide coating increases very rapidly as the thickness of the film increases beyond about 0.3 to 0.4 mil. For comparison with these figures, reference may be made to the abrasion resistance of enamel and varnish coats

such as are applied in finishing metal furniture and office equipment. A typical finish of this type, consisting of primer, two ground coats, graining coat and three coats of finishing varnish, having a total thickness of 3 mils, showed with one sample an abrasion resistance of 306 revolutions, and a somewhat different finish of the same thickness showed an abrasion resistance of 1,095 revolutions. For equivalent thicknesses, therefore, the oxide coat is substantially harder than the baked enamel just mentioned.

Oxide films not over 0.1 to 0.3 mil in thickness, on thin sheet can be readily formed into bottle caps and similar articles. The oxide films, of course, crack on bending, but the cracks are so minute as to be generally undetectable except under the microscope, and the adhesion of the oxide coat to the metal is so perfect that no flaking occurs even when these cracks are present. These minute cracks appear to have very little, if any, effect on the insulating value of the coating. Tests so far indicate that the oxide coat does not affect unfavorably the fatigue strength of the base metal.

As has been already mentioned, oxide coatings may be applied to aluminum by chemical dip methods without the use of current. Such coatings, while usually relatively thin, nevertheless have been used commercially, both in the United States and abroad, for their insulating value. Because of their characteristics, they are only of use when subjected to low voltages; therefore they find their greatest application in motor fields coils and similar applications where the voltage drop between the conductors is low.

Certain types of oxide coatings are very absorbent and can be readily colored by dyes and mineral pigments. These methods of coloring the oxide coatings open up interesting possibilities in the electrical industry. Wires may be colored, for example, to indicate polarity of direct current. Where several wires are in a single conduit, the colors may be used to mark the various circuits. For rapid heat dissipation, busbars and other conductors may be colored black. The bottoms of aluminum utensils for use on electric stoves may be colored black for better heat absorption. The commercialization of these plain and colored "alumilite" finishes in the electrical industry is already under way. Oxide-coated and colored nameplates are finding increasing use. A tremendous number of aluminum flashlight cases in attractive colors have been manufactured. Practically the entire electric refrigerator industry has turned to the use of aluminum refrigerator trays and grids with the plain anodic coating. It is quite evident that these finishes are going to be of increasing value to the electrical industry in the future.

Calculation of Inductance and Current Distribution in Low-Voltage Connections to Electric Furnaces

BY C. C. LEVY*

Non-member

Synopsis.—The special nature of the low-voltage circuit to electric furnaces is emphasized. The conductors employed vary in arrangement and cross section, and are relatively short. The very large currents carried give rise to reactive drops of greater magnitude than is usually supposed. For these reasons a detailed study of the inductance of such circuits is desirable.

Fundamental theorems for deriving geometrical mean distances are first stated, leading to the well-known formulas for self- and mutual-inductance of circular and rectangular sections.

Practical applications of these formulas to the problem of calculating the approximate reactive drop in three-phase arc furnace circuits are worked up in great detail. The same calculations can be used to determine the approximate operating power factor of the furnace.

Unequal current distribution in multiple conductors, due to proximity and skin effects is discussed.

THE problem of calculating the inductance of electric furnace circuits so as to determine the reactive drop is one of considerable practical importance. Although the connections used are made as short as possible, the very large currents involved cause reactive drops which are very considerable and cannot be neglected by the designing engineer.

From the point of view of the designing engineer the value of such calculations consists in the ability which they give to predetermine the approximate power factor of the circuit. This is of importance because the thermal energy developed by the furnace depends only on the kilowatts delivered to it. Therefore, if the circuit has excessive reactance the power factor will be low, and equipment of greater kilovoltampere capacity is needed than would be necessary if the reactance were held to a reasonable figure. Low power factors also concern the power company when energy is purchased and will often materially increase the cost of power.

From another standpoint a certain amount of reactance is necessary and often purposely added for stabilizing the circuit. In such cases it is important to so design the circuit as to provide the reactance in the leads where possible and thus save the additional expense of reactors.

Problems of inductance of circuits and calculations of line reactance are familiar to engineers concerned with transmission lines. However, the physical conditions surrounding the electric furnace circuit are so diametrically opposite to those of the transmission line, that the same methods and formulas do not apply. In the first place transmission line reactances are figured as so many ohms per mile. In the electric furnace circuit on the other hand reactance is figured in ohms per centimeter or per inch. Again the transmission line is figured as a circuit of uniform cross section, in which the conductors are usually circular in section. Such circuits do not present the problems of variation in cross section and arrangement that are found in the electric furnace circuit, where connections are made up of straps varying in number, size and spacings, and where conductors such as flexible cables are bunched together in a restricted space so that proximity effects must be considered, and current distribution between conductors may become quite unequal. These reasons coupled with the magnitude of currents usually handled, make the furnace circuit a unique one.

Fundamental Formulas

The formulas for figuring self- and mutual-inductance of parallel rectangular conductors are derived from the

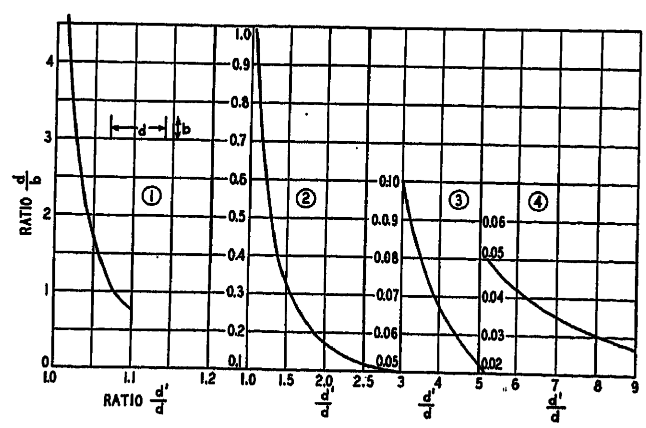

FIG. 1—CURVE SHOWING GEOMETRIC MEAN DISTANCE BETWEEN THIN STRAPS

Based on Formula 132. Bulletin 169, Bureau of Standards

formulas for self- and mutual-inductance of straight cylindrical wires. A cylindrical wire may be assumed composed of an infinite number of filamentary wires or "elements." The self-induction of such a wire is defined as the integration of the infinite number of mutual inductances of every element to itself and to every other element of the conductor. Since the logarithm of the distance between the centers of each pair of elements is involved in the calculation of the mutual inductance of each individual pair, we find that all inductance calculations involve the summation of the logarithms of these distances. The expression "geometrical mean distance" is used to designate this summation.

It is thus seen that this quantity termed geometrical

*General Engr., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

mean distance or g.m.d., as it is usually written, is the basis of our calculations.

Geometrical Mean Distance

This device for figuring self- and mutual-inductance was first introduced by Maxwell and has been used extensively since his time. The definition usually given of the g.m.d. either of a conductor from itself or from another conductor is not clear without some amplification. This definition states that the g.m.d. of a point P from a line is the nth root of the product of the n distances from the point P to the various points on the line, n being increased to an infinite value in determining the value of the g.m.d. To explain this we shall first state, and later prove, the formula for self-inductance of a filamentary cylindrical wire. The formula is

$$M = 2s\left(\log^* \frac{2s}{r} - 1\right)$$

where s is the length of the filament and r is the radius of the wire.

In applying this to the problem of determining the self-inductance of thin straight strips we make use of the theorem that the self-inductance of the circuit is equal to the sum of the mutual inductances of every element to itself and to every other element of the circuit. If we assume that there are n elements and further assume that the current is uniformly distributed then each element carries $\frac{1}{n}$th of the current. The total number of pairs of n elements in all the possible combinations is n^2 so that the value of the self-inductance is the average value of the n^2 elementary inductances. Now each elementary mutual inductance is given by the formula

$$M = 2s\,(\log 2s - \log d - 1)$$

in this expression the first and third terms are constant while the middle term is the logarithm of d, where d represents the n distances between the n^2 pairs of elements. If the average value of this logarithm be found, it will obviously enable the self-inductance of the strip to be calculated. As a result the formula for a thin strip will be represented by

$$L = 2s\left(\log \frac{2s}{R} - 1\right)$$

where $\log R$ = average value of the quantity $\log d_1 + \log d_2 + \log d_3 + \ldots \log d_n$ in which $d_1, d_2 \ldots$ represent the n distances between the elements. The average value of this quantity will be

$$\log R = \frac{1}{n} \log\,(d_1 d_2 d_3 \ldots d_n)$$

or

$$R = \sqrt[n]{d_1 d_2 d_3 \ldots dn}$$

*All logarithms throughout the paper are to base ϵ.

So that the reason for the definition of R as the nth root of the product of the n distances between all the pairs of points in the line of length s representing the cross section of a very thin strip is now apparent. This formula

$$L = 2s\log\left(\frac{2s}{R} - 1\right)$$

can readily be established from first principles.

The above illustration has been used to fix the physical meaning of the term g.m.d. so that it will not become an arbitrary number to be determined and applied in the succeeding formulas for self- and mutual-inductance.

Methods for Finding G.M.D.

Limitations of space prevent the logical theoretical development at this time of the methods for finding g.m.d. This subject is treated in a general way by Gray,† but it is necessary to apply his general equations

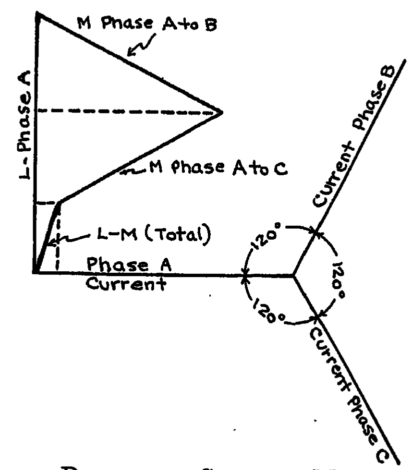

Fig. 2—Vector Diagram of Self- and Mutual-Inductances

to the particular cases in which we are interested. There are also a few typographical errors in Gray's equations, and a lack of that detail of mathematical development which would assist the reader.

G.M.D. of Rectangular Sections

The theorem applying to g.m.d. of two parallel lines from each other is the basis for determining the mutual-induction of thin parallel straps. The cross section of these straps can be represented by the two parallel lines, and their g.m.d. R is given by the formula

$$\log R = \frac{d^2}{b^2}\log d + \frac{1}{2}\left(1 - \frac{d^2}{b^2}\right)\log\,(d^2 + b^2) + 2\,\frac{d}{b}\tan^{-1}\frac{b}{d} - \frac{3}{2} \qquad (1)$$

Where d is the spacing and b the width of the strap. This is equation 132 given in Bulletin 169 of the Bureau of Standards. It is used to determine the g.m.d. be-

†See Gray's Absolute Measurement in Electricity Vol. II, Part I.

tween parallel straps which in turn is used to calculate their mutual inductance.

The determination of the g.m.d. of a rectangular area from itself which is used in the formula for self-induction of a rectangular bar, is derived from the general equation for the g.m.d. of two parallel coplanar rectangles from each other. The general equation for this case is a very lengthy one, which reduces, for the special case of a rectangular area to itself, to the formula

$$\log R = \frac{1}{2}\log\left(a^2+b^2\right) - \frac{1}{12}\frac{b^2}{a^2}\log\left(1+\frac{a^2}{b^2}\right) - \frac{1}{12}\frac{a^2}{b^2}\log\left(1+\frac{b^2}{a^2}\right) + \frac{2}{3}\frac{b}{a}\tan^{-1}\frac{a}{b} + \frac{2}{3}\frac{a}{b}\tan^{-1}\frac{b}{a} - \frac{25}{12} \qquad (2)$$

Where a and b are the length and breadth of the rectangle.

However, this equation need not be used in numerical calculations since it has been found that there exists a very simple relation between the g.m.d. and the perimeter of a rectangle.

The table given below is taken from the Bureau of Standards Bulletin 169 and shows that for various ratios as a the length, to b the breadth of the rectangle the g.m.d.

$$R \text{ is very nearly equal to } 0.2235\,(a+b) \qquad (3)$$

This simple formula is used for determining the g.m.d. of a section.

TABLE I—GEOMETRIC MEAN DISTANCES OF RECTANGLES

Ratio	R	$\frac{R}{a+b}$
1.0 :1	0.44705a	0.22353
1.25:1	0.40235a	0.22353
1.5 :1	0.37258a	0.22355
2 :1	0.33540a	0.22360
4 :1	0.27961a	0.22360
10 :1	0.24596a	0.22360
20 :1	0.23463a	0.22346
1 :0	0.22315a	0.22315

Working formulas for rectangular sections are

(1) G.m.d. of rectangular section on itself

$$R = 0.2235\,(a+b) \qquad (3)$$

(2) G.m.d. of rectangular sections from each other

$$\log R = \frac{d^2}{b^2}\log d + \frac{1}{2}\left(1-\frac{d^2}{b^2}\right)\log\left(d^2+b^2\right) + 2\frac{d}{b}\tan^{-1}\frac{b}{d} - \frac{3}{2} \qquad (1)$$

G.M.D. of Circular Conductors

By reference to the theoretical treatment of g.m.d. for circular areas we find the g.m.d. between two circular areas is the physical distance between the centers of the two areas, or $R = d$.

In the case of a circular area from itself

$$\log R = \log r - \frac{1}{4}$$

or

$$R = r\epsilon^{-\frac{1}{4}} = 0.779r \qquad (4)$$

Where r is the radius of the conductor.

These two equations are used in figuring the self- and mutual-inductance of cylindrical conductors.

Self-Inductance of Two Parallel Cylindrical Conductors

This is given by the well-known formula

$$L = 2\log\frac{D}{r} + \frac{\mu}{2} \qquad (5)$$

Where L is the self-inductance per cm. length of each wire. The first term of this equation is the inductance due to the external flux while the second represents the inductance due to internal flux of conductor with permeability $= \mu$.

If the conductor instead of being solid were a tube with a wall of infinitesimal thickness, the flux inside the conductor could be neglected so that the inductance of the conductor would be $2\log\frac{D}{r_1}$ where r_1 is radius of the tube with equivalent inductance. Since these two expressions for inductance are equal.

$$2\log\frac{D}{r_1} = 2\log\frac{D}{r} + 2\log\epsilon^{0.25} = 2\log\frac{D\,(\epsilon^{0.25})}{r}$$

So that

$$r_1 = 0.779r \qquad (6)$$

This is the expression for the g.m.d. of a circular area from itself. We can thus eliminate consideration of the internal flux by using the g.m.d. of the circular area from itself instead of r the physical radius of the conductor.

The inductance per cm. length is therefore

$$L = \frac{D}{r_1}$$

where r_1 is the g.m.d. of the conductor.

If the return circuit be considered infinitely distant the following equation in terms of length s and radius r will be found more convenient.

$$L = 2s\left(\log\frac{2s}{r} - \frac{3}{4}\right) \qquad (7)$$

Mutual-Inductance of Two Parallel Cylindrical Wires

The mutual inductance of two parallel wires of length s, radius r and distance apart d will be the number of lines of force due to unit current in one which cut the other when the current disappears.

In considering the self-inductance of a single wire, we found that the number of lines N outside the wire which will collapse upon the wire when the current stops, is found by integrating between the limits $x = r$ and $x = \infty$. In this case however the flux between the wires is ineffective because it produces effects which neutralize each other, so the integration is made between the limits $x = d$ and $x = \infty$.

Thus

$$M = 2\left[s\,\frac{\log s + \sqrt{s^2 + d^2}}{d} - \sqrt{s^2 + d^2} + d\right]$$

$$= 2s\left[\log\frac{2s}{d} - 1 + \frac{d}{s}\right] \qquad (8)$$

Self-Inductance of a Straight Rectangular Bar

The self-inductance of a bar with rectangular cross section is the same as the mutual inductance of two parallel straight filaments of the same length separated by a distance equal to the g.m.d. of the cross section of the bar.

$$L = 2s\left(\log\frac{2s}{R} - 1 + \frac{R}{s}\right) \qquad (9)$$

Note that in this formula the g.m.d. R replaces the distance d in formula (8). The reason of course is that the physical distance between centers in the case of cylindrical conductors is equal to the g.m.d., whereas with the rectangular sections the distance between centers must be replaced by the g.m.d. of the section to itself. R in this formula is readily obtained from equation (3), which gives

$$R = 0.2235\,(a + b)$$

Where a is the length and b the width of the rectangular section.

Mutual-Inductance of Two Parallel Rectangular Straps

The equation for this case is merely a modification of equation (8) in which the distance d between conductors is replaced by d' the g.m.d. between the rectangular areas.

Hence

$$M = 2s\left[\log\frac{2s}{d'} - 1 + \frac{d'}{s}\right] \qquad (10)$$

This equation is very frequently used.

Multiple Conductors

All formulas so far have been concerned with a single conductor either circular or rectangular in section. However, the conductors met with in practise consist of a number of individual conductors connected in parallel. The calculations must therefore be modified to take this into consideration. One method is to find the mutual inductance of each conductor with respect to every other conductor in the multiple conductor and also with respect to itself, and then take the average of these mutual inductances. This is, however, a tedious job, and for most numerical calculations, except when buses are interlaced, it is simpler to replace the multiple conductor by an equivalent single conductor with a thickness equal to the sum of the thickness of the individual

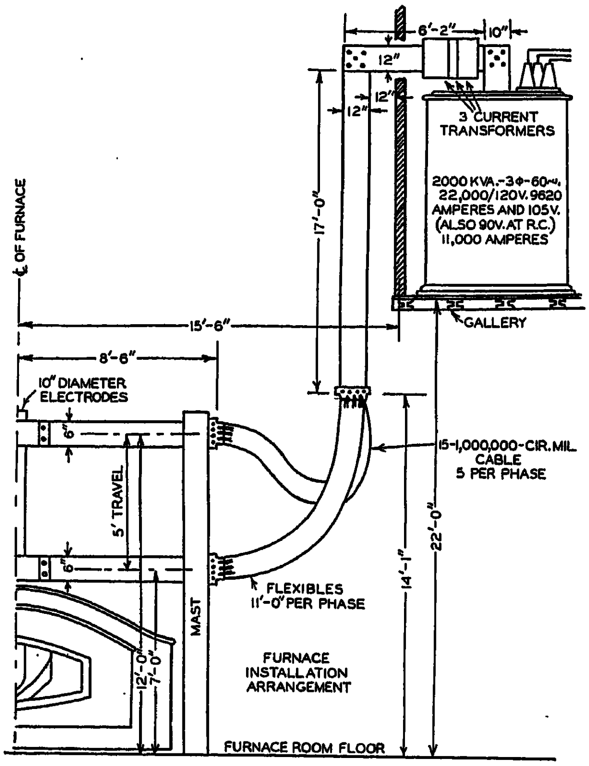

Fig. 3—Arrangement of 2,000-Kva. Furnace Circuit

straps plus the distance between the straps, provided these distances are small compared to the width of the bar. This method is not used for interlaced connections because it is necessary to find the algebraical sum of the various individual inductances between straps, since adjacent straps carry current in opposite direction.

In the following examples inductance has been expressed in terms of centimeters. To be strictly correct this should be centimeter flux lines, since inductance may be defined as the flux linking the total circuit per unit of total current. This value of centimeters flux lines must be multiplied by 10^{-9} to reduce to henrys.

Practical Applications

In order to show how the foregoing principles and formulas may be applied to actual problems two circuits will be worked out in detail. Both of these are for existing installations and actual measurement of the

impedance drop will be given as a check on the methods of calculation.

Example I

The first furnace circuit has star-connected secondary leads of rather special arrangement. Because of constructional difficulties the furnace transformer was located in a transformer vault about 22 ft. above the furnace floor. The vertical leads from the transformer are interlaced for a distance of 17 ft. The interlacing, however, is not of the usual type, because the star is closed at the transformer thus eliminating the return conductors, and the phases are alternated thus a_1, b_1, c_1, a_2, b_2, c_2, etc., so that the mutual reaction between adjacent straps is between two straps in different phases rather than between two straps in the same phase, carrying current in opposite directions, as would be done in the usual type of interlaced circuit.

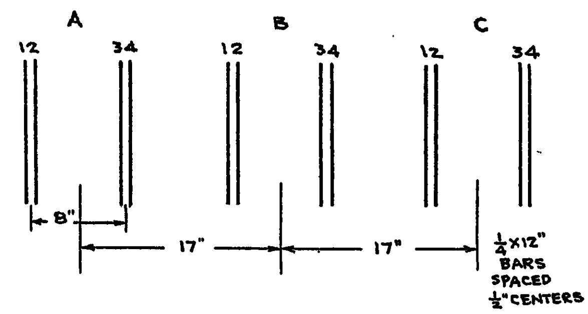

Fig. 4—Horizontal Leads from Transformer

Fig. 3 shows the general arrangement of the low-voltage bus layout. Since the measured drop was taken from a point close to the transformer terminals to the top of the electrodes, only the following sections will be calculated.

Section 1—Horizontal leads from transformer
Section 2—Interlaced bus
Section 3—Flexibles
Section 4—Copper bus on furnace

Section 1 consists of twelve 12 in. x ¼ in. straps arranged as shown in Fig. 4. To simplify calculation consider the two ¼ in. x 12 in. bars separated on ½ in. centers in each group as equivalent to one conductor ¾ in. x 12 in. This will make each phase consist of two parallel conductors ¾ in. x 12 in.

Self-inductance of either bar is given by formula

$$L = 2s\left(\log\frac{2s}{R} - 1 + \frac{R}{S}\right)$$

Where

S = 6 ft. - 2 in. = 188 cm.

R = g.m.d. of bar is given by the formula R = 0.2235 $(a + b)$ = 0.2235 × 12.75 = 7.25 cm.

L therefore = 376 × 2.984 = 1,120 cm.

The mutual-inductance of straps at various separations is given by equation (10)

$$M = 2s\left(\log\frac{2s}{d'} - 1 + \frac{d'}{s}\right)$$

Where d' is the g.m.d. between the straps and s is the length in cm.

In order to find d' the g.m.d. between the straps readily curve Fig. 1 has been prepared from the formula giving the g.m.d. between rectangular sections. The ratio of $\frac{d'}{d}$ where d is the distance between straps and d' the g.m.d. is given for various values of the ratio $\frac{d}{b}$. By referring to this curve the g.m.d. for various values of $\frac{d}{b}$ can readily be found. Curve Fig. 5 has then been drawn by calculating a few values of M for various separations between bars of this particular section. The mutual inductance for any two straps can then be determined from the curve without further calculation. From Fig. 2 showing the vector relation between the inductances of the phases, we see that we must combine the inductance of phase A vectorially

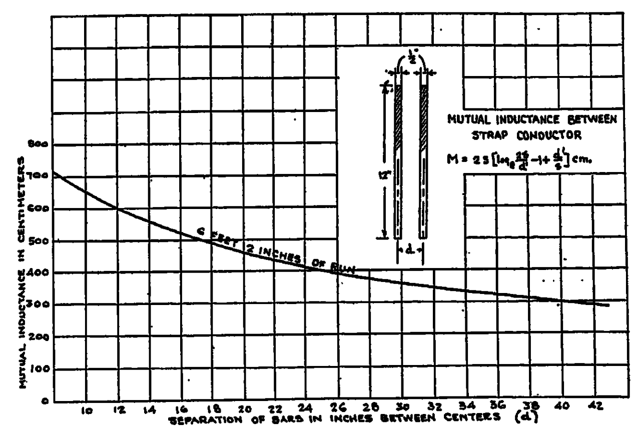

Fig. 5—Curve Showing Mutual-Inductance Between Straps for Section No. 1

with that of phases B and C in order to get the total inductance.

$$\text{Total inductance} = L_A - \frac{1}{2}M_{AB} + j\ .866\ M_{AB} - \frac{1}{2}M_{AC} - j\ .866\ M_{AC}$$

Lead (12) *A*			
Self-inductance		1120 + *j*0	
Mutual from *A* (34)	separation 8 in.	707 + *j*0	
Mutual from *B* (12)	separation 17 in.		− 253 + *j* 439
Mutual from *B* (34)	separation 25 in.		− 205 + *j* 355
Mutual from *C* (12)	separation 34 in.		− 171 − *j* 296
Mutual from *C* (34)	separation 42 in.		− 150 − *j* 260
		1827	− 779 + *j* 238
			= 1048 + *j* 238

Leads (3.4) A

Self-inductance	1120 $+j0$	
Mutual from A (12) separation 8 in.	707 $+j0$	
Mutual from B (12) separation 9 in.		$-338+j585$
Mutual from B (34) separation 17 in.		$-253+j439$
Mutual from C (12) separation 26 in.		$-200-j346$
Mutual from C (34) separation 34 in.		$-171-j296$
	1827	$-962+j382$
		$=865+j382$

The average of these two values $= 957 + j310$

Since the two groups are connected in parallel

the total for phase A $= 478 + j\,155$

Phase B by a similar calculation $= 389 + jo$

Phase C same as phase A $= 478 - j\,155$

Section 2 consists of a 17-ft. run of interlaced connections shown in Fig. 6.

Self-inductance of one bar

$$L = 2S\left(\log \frac{2S}{R} - 1 + \frac{R}{S}\right)$$

$$= 4150 \text{ cm.}$$

Mutual-inductances for various distances between bars are given in curve Fig. 7.

Mutual-inductance of phase A (4 parallel-connected bars) to other two phases and to itself, using curve Fig. 7 and tabulating will be

is given by formula

$$L = 2S\left(\log \frac{2S}{R} - \frac{3}{4}\right)$$

$$R = 3 \times 2.54 = 7.62 \text{ cm.}$$

$$S = 335 \text{ cm.}$$

$$L = 2490 \text{ cm.}$$

Mutual-inductance for circular area is given by equation (8).

$$M = 2s\left(\log \frac{2s}{d} - 1 + \frac{d}{s}\right)$$

Therefore mutual from phase A to phase B

$$= 670\left(\log \frac{670}{54.4} - 1 + \frac{54.4}{335}\right)$$

$$= 1110 \text{ cm.}$$

Similarly M from C to A = 764 cm.

$$\begin{aligned} \text{Resultant inductance of phase } A = &+ 2490 + j0 \\ &- 555 + j961 \\ &- 382 + j662 \\ \hline &+ 1553 + j299 \end{aligned}$$

M from	To Bar A_1	To Bar A_4	To Bar A_7	To Bar A_{10}
$B2$	$-2030+j3520$	$-1940+j3360$	$-1710+j2980$	$-1552+j2690$
$C3$	$-1940-j3360$	$-2030-j3520$	$-1777-j3080$	$-1599-j2770$
$B5$	$-1777+j3080$	$-2030+j3520$	$-1940+j3360$	$-1710+j2980$
$C6$	$-1710-j2980$	$-1940-j3360$	$-2030-j3520$	$-1777-j3080$
$B8$	$-1599+j2770$	$-1777+j3080$	$-2030+j3520$	$-1940+j3360$
$C9$	$-1552-j2690$	$-1710-j2980$	$-1940-j3360$	$-2030-j3520$
$B11$	$-1478+j2560$	$-1599+j2770$	$-1777+j3080$	$-2030+j3520$
$C12$	$-1452-j2520$	$-1552-j2690$	$-1710-j2980$	$-1940-j3360$
	$-13538+j380$	$-14578+j180$	$-14914+j0$	$-14578-j180$

M from		M from		M from		M from	
$A4$	$+2710$	$A1$	$+3710$	$A1$	$+3300$	$A1$	$+3026$
$A7$	$+3300$	$A7$	$+3710$	$A4$	$+3710$	$A4$	$+3300$
$A10$	$+3026$	$A10$	$+3300$	$A10$	$+3710$	$A7$	$+3710$
	14186		14870		14870		14186
	$-13538+j380$		$-14578\quad j180$		$-14914+j0$		$-14578-j180$
	$+648+j380$		$+292+j180$		$-44+j0$		$-392-j180$

Phase A average inductance $= \dfrac{\Sigma\ (L+M)}{4}$

$= +126 + j94$

Phase C being symmetrical with A $= +126 - j94$

Phase B calculated in same way as A $= +68.5 + j0$

Section 3—Flexible Cables to Furnace.

Total length = 11 ft. = 335 cm.

Each phase consists of fifteen 1,000,000-cm. cables

Separation of flexibles 17 in. centers at start

27 in. centers on furnace

Equivalent separation $= \sqrt{17\text{x}27} = 21.4$ in. $= 54.4$ cm.

L for cables approximately diameter = 6 in.

Phase C is symmetrical with phase A $= +1553 - j299$

$$\begin{aligned} \text{Phase } B = &+ 2490 + j0 \\ &- 555 + j961 \\ &- 555 - j961 \\ \hline &+ 1380 + j0 \end{aligned}$$

Section 4—Bus on Furnace. The actual arrangement of these buses is shown in Fig. 8.

In order to make the calculation shorter and less complicated consider the group of 4 conductors of each group with ¼ in. between each strap as equivalent to a single conductor of cross section 6 in. x 1 ¾ in. located on the center line of the group. Each phase will then consist of two groups of conductors each 6 in. x 1 ¾ in. and 5 in. apart.

Length of run = 6 ft. 7 in. = 200 cm.
Self-inductance of A_1

$R = 0.2235\,(6 + 1.75) = 1.73 \text{ in.} = 4.4 \text{ cm.}$

$$L = 400\left(\log \frac{400}{4.4} - 1 + \frac{4.4}{200}\right)$$

$$= 400 \times 3.532 = 1413 \text{ cm.}$$

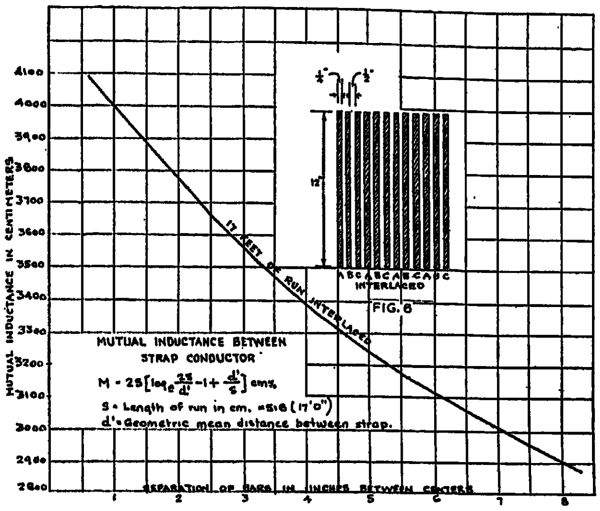

FIG. 6—ARRANGEMENT OF VERTICAL INTERLACED BARS
FIG. 7—CURVE SHOWING MUTUAL-INDUCTANCE BETWEEN STRAPS FOR SECTION NO. 2

The self-inductance and mutual-inductances for various separations between bars are tabulated below.

Lead $A1$

Self-inductance	1413 + j0
Mutual from $A2$ separation 5 in.	936 + j0
Mutual from $B1$ separation 22 in.	−247 + j425
Mutual from $B2$ separation 27 in.	−220 + j380
Mutual from $C1$ separation 56 in.	−148 − j256
Mutual from $C2$ separation 61 in.	−145 − j250
Total	1589 + j299

Lead $A2$

Self-inductance	1413 + j0
Mutual from $A1$ separation 5 in.	936 + j0
Mutual from $B1$ separation 17 in.	−285 + j495
Mutual from $B2$ separation 22 in.	−247 + j425
Mutual from $C1$ separation 51 in.	−155 − j268
Mutual from $C2$ separation 56 in.	−148 − j256
Total	1514 − j376

Average inductance of phase A = ½ the average of the two values = 751 + j174.

Phase B could be calculated in the same way. It should be noted that phase C will not in this case be the the same as phase A since the two spacings are not symmetrical.

The total inductance of phase A can now be tabulated.

Section	Inductance in cm.
1	478 + j155
2	126 + j 94
3	1553 + j299
4	751 + j174
Total	2908 + j722

The j component represents an actual energy component.

$$\text{The inductive reactance} = 2\,\pi f L \times 10^{-9}$$
$$= 377 \times 2908 \times 10^{-9}$$
$$= 0.0011 \text{ ohms}$$

Test results—measured impedance drops on phase A.

Reading	Amperes	Volts
1	7,500	8.5
2	7,700	9
3	7,400	8.5
4	8,000	9.5
Average	7,650	8.9 volts

Calculated reactance—0.0011 ohms.
Drop when carrying 7650 amperes = 8.4 volts.
Resistance drop = 0.2 volts.
Impedance drop = 8.4 volts (approximately).

This compares with the measured drop within reasonable limits of accuracy, taking into consideration the fact that measured impedances when large currents are involved are not precise measurements.

Theoretically phase C should have the same inductance as phase A but since the j components for phase C are opposite in direction to phase A the actual drops will not be the same. A further unbalance exists in this case, since the neutral is not connected to the shell of the furnace. The average of several readings for phase C was found by test to be 7 ½ volts, the average current being 8,000 amperes.

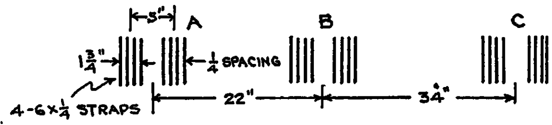

FIG. 8—ARRANGEMENT OF COPPER STRAPS ON FURNACE

If the approximate per cent reactance and power factor of the circuit is desired it would be necessary to include the inductance of the electrodes in the calculations. This would bring the total inductance to about 3700 + j789. Low tension voltage 120 volts Y = 69.3 volts to neutral.

Transformer reactance drop = 8.1 per cent = 5.62 volts
Current = 9620 amperes at 2000 kva.

$$\text{Lead reactance} = 377 \times (3700 + j789)$$
$$= 0.00139 + j0.000297 \text{ ohms}$$

$$\text{Total voltage drop at 120 volts} = \text{transformer} + \text{leads}$$
$$= 5.62 + 13.4 + j2.9$$
$$= 19 + j2.9 \text{ volts}$$

$$\text{Per cent reactance} = \frac{19}{69.3} \times 100 = 27.4 \text{ per cent}$$

Power factor = 96 per cent
j unbalance = 4.2 per cent

EXAMPLE II

For this example a furnace with delta-connected secondary was chosen, the low-voltage leads being arranged as shown in Fig. 9.

In this example the portion of the low-voltage bus across which impedance drop was measured does not include any interlaced connections.

Section 1—Horizontal run on top of furnace. (Straight portion)

Section 2—Horizontal run on top of furnace. (Curved portion)

Section 3—Vertical run on furnace to point at which flexibles are connected.

Section 4—Flexible connections.

Section 5—Horizontal run from flexible leads to point at which transformer cables are connected.

Section 1—For arrangement of straps see Fig. 10.

Length $= 44 \times 2.54$ cm.
$= 112$ cm.

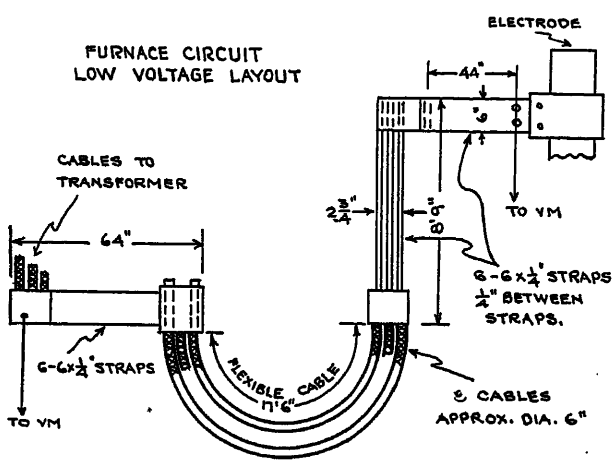

FIG. 9—ARRANGEMENT OF FURNACE CIRCUIT

Self-inductance phase A

$$L = 2S\left(\log\frac{2S}{R} - 1 + \frac{R}{S}\right) = 224 \times 2.8553$$
$$= 640 \text{ cm.}$$

$R = 223\,(6 + 2.75) \times 2.54$ cm.
$= 4.95$ cm.

For mutual of A from B we have 22 in. separation

$$\frac{d}{b} = \frac{22}{6} = 3.66 \text{ from curve Fig. 1 } \frac{d'}{d} = 1.02$$

$$d' = d \times 1.02 \times 2.54$$
$$= 57 \text{ cm.}$$

$$M = 224\left(\log\frac{224}{57} - 1 + \frac{57}{112}\right)$$
$$= 224 \times 0.8861 = 198 \text{ cm.}$$

For mutual from A to C 44 in. separation.

$$\frac{d}{b} = \frac{44}{6} = 7.33 \text{ therefore } d' = 44 \times 2.54$$
$$= 112 \text{ cm.}$$

$$M = 224\left[\log\frac{224}{112} - 1 + \frac{112}{112}\right]$$
$$= 224 \times 0.693 = 155 \text{ cm.}$$

Total inductance phase A for Section 1

Self-inductance $= 640 + j0$
Mutual A to B $= -99 + j172$
A to C $= -78 - j134$
$463 + j38$

Section 2 is a continuation of Section 1 but with variable spacing between buses. Initial separation = 22 in., final separation = 10 in. equivalent separation,

$= \sqrt{10 \times 22} = 14.8$ in.
length $= 24$ in. $= 61$ cm.

$$L = 122\left[\log\frac{122}{4.95} - 1 + \frac{4.95}{61}\right]$$
$$= 122 \times 2.2843$$
$$= 278 \text{ cm.}$$

For M from A to B separation $= 14.8$ inches

$$\frac{d}{b} = \frac{14.8}{6} = 2.46 \qquad \frac{d'}{d} = 1.04$$

$$d' = 1.04 \times 14.8 \times 2.54 = 39 \text{ cm.}$$

$$M = 122\left[\log\frac{122}{39} - 1 + \frac{39}{61}\right]$$
$$= 122 \times 0.7842 = 96 \text{ cm.}$$

For M from A to C separation $= 29.6$ in.

$$d' = 29.6 \times 2.54 = 75 \text{ cm.}$$

$$M = 122\left[\log\frac{122}{75} - 1 + \frac{75}{61}\right]$$
$$= 122 \times 0.7186$$
$$= 88 \text{ cm.}$$

Total inductance phase A for this section

Self-inductance $= 278 + j0$
Mutual A from B $-48 + j83$
Mutual A from C $-44 - j76$
$186 + j7$

Section 3—Vertical run on furnace.

Six 6 in. by ¼ in. straps on 10 in. centers

Length $S = 105$ in. $= 256$ cm.

$$L = 2S\left[\log\frac{2S}{R} - 1 + \frac{R}{S}\right]$$

$R = 223 \times (6 + 2.75) \times 2.54$

$L = 532 \times 3.6915$

$= 1963$ cm.

For mutual of phase A from phase B

$\frac{d}{b} = \frac{10}{6} = 1.6 \quad \frac{d'}{d} = 1.05 \quad d' = 1.05 \times 10 \times 2.54 = 26.8$

$$M = 532\left(\log\frac{532}{26.8} - 1 + \frac{26.8}{266}\right)$$

$= 532 \times 2.0867 = 1110$ cm.

For M from A to C

$\frac{d}{b} = \frac{20}{6} = 3.33 \quad \frac{d'}{d} = 1.02 \times 20 \times 2.54 = 52$

$$M_{AC} = 532\left(\log\frac{532}{52} - 1 + \frac{52}{266}\right)$$

$= 532 \times 1.5254 = 810$ cm.

Total for phase A = $1963 + j0$
$- 555 + j960$
$- 405 - j700$
$1003 + j700$

Section 4—Flexibles.

Length—17 in. 6 in. = 210 in. = 534 cm.

Diameter = 6 in. Spacing 14 in.

$R = 7.62$ cm.

$$L = 1068\left[\log\frac{1068}{7.62} - \frac{3}{4}\right]$$

$= 4475$ cm.

For mutual A from B, spacing is 14 in. or 35.6 cm.

$$M = 1068\left[\log\frac{1068}{35.6} - 1 + \frac{35.6}{534}\right]$$

$1068 \times 2.4677 = 2640$ cm.

For mutual of A from C spacing = 71 cm.

$$= 1068\left[\log\frac{1068}{71} - 1 + \frac{71}{534}\right]$$

$= 1068 \times 1.841 = 1960$ cm.

For phase A total = $4475 + j0$
$- 1320 + j2280$
$- 980 - j1700$
$2175 + j580$

Section 5.

Length = 64 in. = 163 cm.

Spacing between phases = 14 in.

Each phase 6 straps 5 × ¼ with ¼ in. spacing

Equivalent conductor cross section 6 × 2 ¾ in.

$R = 223 \times (6 + 2.75) \times 2.54 = 4.95$ cm.

$$L = 326\left[\log\frac{326}{4.95} - 1 + \frac{4.95}{163}\right]$$

$= 326 \times 3.22 = 1050$ cm.

For M from A to B we have $\frac{d}{b} = \frac{14}{6} = 2.33$

$\frac{d'}{d} = 1.04 \quad d' = 1.04 \times 14 \times 2.54$ cm.

$= 37$ cm.

$M = 326 \times 1.414 = 460$ cm.

For M from A to C we have $\frac{d}{b} = \frac{28}{6} = 4.66$

$\frac{d'}{d} = 1.015 \quad d' = 28 \times 1.015 \times 2.54 = 72$ cm.

$M = 326 \times 0.9681$

$= 315$ cm.

Total inductance of phase A for Section 5

Self-induction = $1050 + j0$
Mutual A to B = $230 + j400$
Mutual A to C = $-158 - j272$
$662 + j128$

Total-induction for phase A

Section 1	$463 + j38$
Section 2	$186 + j7$
Section 3	$1003 + j260$
Section 4	$2175 + j580$
Section 5	$662 + j128$
	$4489 + j1013$

$X_L = 2\pi f L \times 10^{-9}$

$= 377 \times 4490 \times 10^{-9}$ ohm

$= 0.00169$ ohm

Drop when carrying 8,400 amperes

$= 14.19$ volts

Test reading 13.9 volts impedance drop which agrees within reasonable limits of accuracy.

Test Results

Average of 8 readings on phase A = 4.2 amperes. *CT* ratio 2000/1

Average secondary current = 8,400 amperes

V^m readings of impedance drop phase A

Average of 8 readings = 13.9 volts

Calculated inductive reactance = 0.00169

Calculated reactive drop—14.19 volts

This agrees with the measured impedance drop within reasonable limits of accuracy.

Distribution of Current in Multiple Conductor Buses

The method of geometric mean distances is strictly accurate only when each section of the area of each individual conductor carries the same current. This assumption is not fulfilled in practise, because of the two phenomena usually called "skin effect" and "proximity effect." Skin effect is the result of the variation in the induced e.m.f. in the conductor due to its own field, and results in greater current density in the outer filaments of the conductor than in the inner filaments. As a result a conductor with a thickness much over ¾ is not economical, and for the same reason hollow conductors are superior to solid conductors. The effect on the current distribution in a conductor due to the currents in adjacent conductors, is called "proximity effect." For example the currents in the return conductor in a single-phase circuit and in the other phases of a three-phase circuit materially affect the current distribution of the conductor. Similarly in a multiple conductor the influence of each strap on the others must be considered. Taking the simple case of a single-phase circuit, the field of conductor B cutting conductor A causes a circulating current to flow down one side of the conductor and back along the other side, and this is superimposed on the main current so that the resultant density on the inner side of the conductor is greater than on the outside. However, when the current in the two conductors is in the same direction we find that the current crowds to the outer sides.

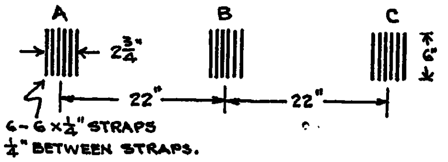

Fig. 10—Arrangement of Horizontal Straps on Furnace

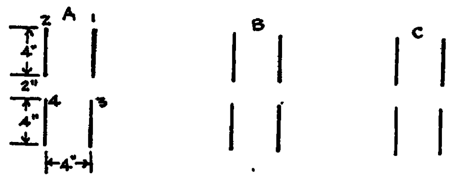

Fig. 11—Three-Phase Modified Hollow Square Bus

In a three-phase circuit the influence of the other two phases can be calculated and the current distribution of the phases determined. By reference to the vector diagram of the three-phase circuit it is seen that the proximity effect of the other two phases is approximately that due to a return current of half value combined with a quadrature component 0.866 in value. This quadrature component being opposite in one phase to what it is in the other will affect the current distribution accordingly.

When the conductors are built up of several spaced bars in parallel the current distribution is influenced by the proximity effect of the other conductors. For example if four straps are used the inner two straps will carry less current than the outer two when the proximity effects of the straps in that phase alone are considered. However, when the effects of the conductors in the other phases are considered the proximity effect will tend to cause the current to crowd to the side of the bar towards the other phases so that the combined effect of these two tendencies will determine the actual current distribution.

This unequal division of current is very materially affected by the spacing between phases. For instance if the distance between buses is doubled, the inequality between currents I_1 and I_2 is reduced almost in the same proportion so that to get the two conductors to divide current equally they should be well separated. As the spacing is decreased the current unbalance becomes greater, and therefore, the copper is not used economically or else part of the bus tends to overheat. In an effort to overcome this tendency a type of bus known as the modified hollow square bus has been advocated. The arrangement of this bus for four straps per phase is shown in Fig. 11. By putting conductors 1 and 3 vertically above each other so that they are the same distance from the conductors of the other two phases they will have practically no proximity effect on each other, and thus divide current equally. The unbalance will then be between the two pairs of conductors 1 and 3 and 2 and 4. Such a bus will carry the same current with less temperature rise than when the straps are arranged in the conventional manner all in line. Some curves illustrating the division of current with such an arrange-

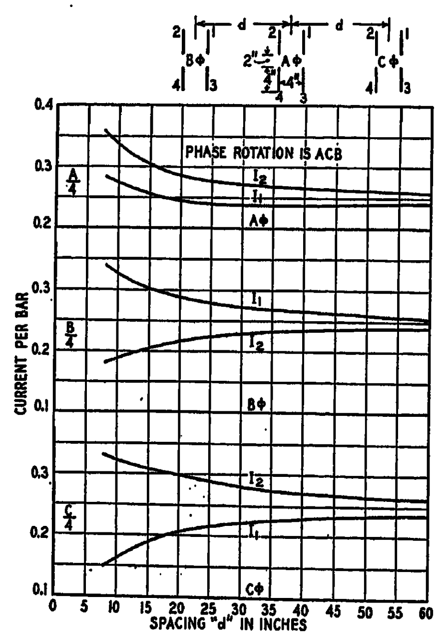

Fig. 12—Distribution of Current in Conductors of Hollow Square Bus

ment with varying spacing between phases emphasizes the necessity for separating the phases when very heavy a-c. currents are handled. This is a point that is seldom considered when low-voltage bus layouts are made, but it is of great importance when uninterlaced heavy capacity buses are to be designed. A bus capacity in excess of 6,000 amperes should not have less than 18 in. spacing.

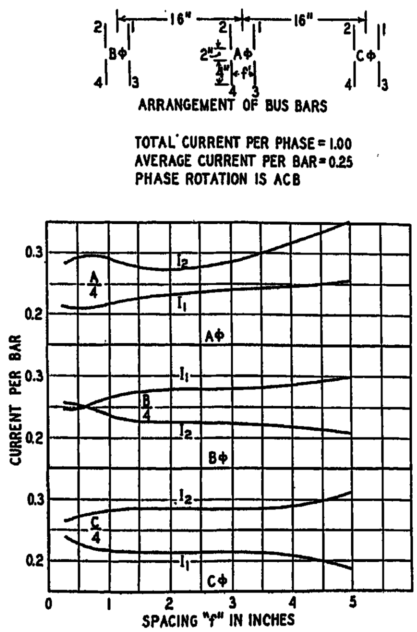

FIG. 13—VARIATION OF CURRENT DISTRIBUTION WITH CHANGE IN SPACING

Fig. 12 illustrates the way in which the unequal division of current in the two groups of bars of a modified hollow square bus will vary with the spacing d between phases. It brings out very clearly the fact that increasing this distance will reduce the difference between the currents I_1 and I_2 in the two groups of bars.

Fig. 13 illustrates the variation of current distribution in the three phases with change in spacing f between the two groups of bars in each phase.

CONCLUSION

In the foregoing analysis of furnace circuits an attempt has been made to give the fundamental equations on which the calculations are based and typical calculations have been made. These calculations do not claim to be precise, but are sufficiently accurate for practical purposes.

They will enable the operating engineer to check approximate per cent reactance so that unnecessary reactance can be avoided. They will also assist the designer in laying out logical and reasonable arrangements of copper for carrying heavy currents and thus avoid subsequent criticism for poor arrangement.

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New Applications of Non-Linear Circuits

To Relay and Control Problems

BY C. G. SUITS*

Non-member

Synopsis.—*The fundamental relations between voltage and current for an iron core reactor are reviewed. The theory of the performance of such reactors in series and parallel resonance circuits may be qualitatively obtained by graphical means. For reactors which have nearly linear properties the graphical method is capable of yielding quantitatively accurate results. A fundamental analogy exists for the properties of series and parallel resonance circuits employing the same inductance and capacitance elements. It is shown that; (a) for the series circuit the current is functionally related to the voltage in the same manner as, for the parallel circuit, the voltage is related to the current, if (b) for the inductance element the current is functionally related to the voltage in the same manner as, for the capacitance element, the voltage is related to the current.*

It is stated that in the series or parallel circuit, means are available for causing the current, as the dependent quantity, to vary as a function of voltage, as the independent quantity, or vice versa. Because of this generalization, the series circuit which is sensitive to voltage changes can also be caused to function as a constant-voltage source, insensitive to current changes. Similarly the parallel circuit, which is sensitive to current changes, can be used as a constant-current source, independent of voltage changes.

The voltage sensitivity of the series circuit and the current sensitivity of the parallel circuit are applied to the problem of voltage and current relays. Such relays are characterized by great sensitivity to small changes in voltage and current, together with sturdy and economical mechanical elements. The special properties of the resonant-current relay adapt it to under-current and under-voltage relay applications.

ELECTRIC circuits comprising inductance, capacitance, and resistance elements in series and parallel resonance networks are fundamentally important to, and widely utilized in, the communication field, but their application to the problems in power transmission and distribution have been relatively limited. These circuits are important for their frequency characteristics, and if the magnitude of the inductance, capacitance, or resistance is independent of the current flowing in the circuit, these frequency-sensitive[1] properties are also independent of voltage or current. Circuits of this type may be said to be *frequency-sensitive, voltage-insensitive,* to distinguish them from another type of circuit about to be described.

This latter type of circuit similarly comprises reactive and resistive elements, but these elements are characterized by a dependence of the magnitude of the inductance, capacitance, or resistance upon current. Circuits employing elements of this general nature, of which an inductance with a closed iron core is a well-known and important example, will be referred to as *non-linear circuits.* This terminology is suggested by their alternating current volt-ampere characteristics which are convenient criteria of the kind and degree of non-linearity. There is a surprisingly large variety of non-linear inductances, resistances and capacitances, and of course the number of possible series and parallel combinations is very great.

It is intended to describe two fundamentally important non-linear circuits, and to show how the unusual properties of these circuits have a natural application to some of the problems in the field of electric power distribution and utilization.

The particular circuits in question employ a linear resistance (in the sense referred to above), a linear capacitance, and a non-linear inductance. The non-linearity of the latter is due to the iron present in the core material. Under certain conditions the flux density B in this core material is related to the magnetizing force H in the manner shown by the curves of Fig. 1, which were taken for a sample of silicon transformer steel. The flux density is thus an involved function of

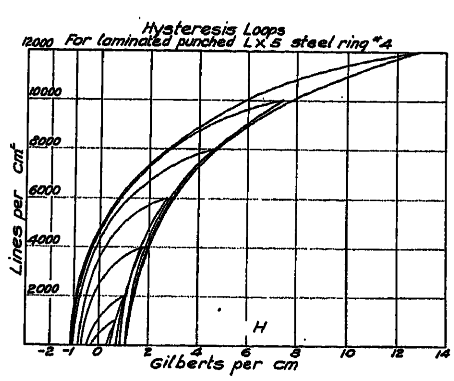

FIG. 1

the magnetizing force, and because of this fact accurate analytical expression of the properties of circuits employing saturating reactors is attended with great difficulty. When this reactor is used as a circuit element, it is important to know how the inductance is related to the current. The instantaneous value e of the voltage between the terminals of the reactor is proportional to the rate of change of the flux ϕ through the windings,

$$e = K\frac{d\phi}{dt} = K\frac{d\phi}{di}\frac{di}{dt} = K_1\frac{dB}{dH}\frac{di}{dt}$$

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1. In referring to the properties of circuits, *sensitive* is used here and subsequently to denote the ratio between the percentage change in the *dependent* quantity that follows from a certain percentage change in the *independent* quantity. Thus, a frequency-sensitive circuit is one for which the percentage change in current is large for a small percentage change in frequency.

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where i is the current, t the time, and K, K_1 are factors which depend upon the geometry.

It is assumed that all the flux is concentrated in the core material, that the distribution of flux is uniform, and that the resistance of the winding is negligibly small. These things are seldom true in practical cases. For a linear or constant inductance the coefficient $\frac{dB}{dH}$ would be proportional to the inductance; for this iron core reactor,

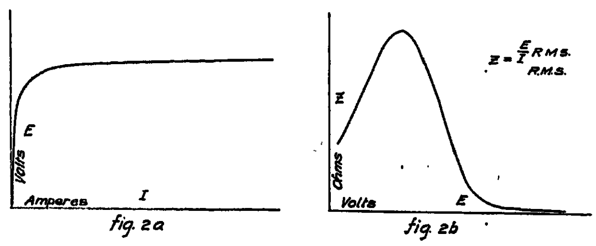

Fig. 2

$$K\frac{d\phi}{di}\left(\text{proportional to}\frac{dB}{dH}\right)$$

may be called the *incremental inductance*,[2] defined as

$$K\frac{d\phi}{di} = K\lim_{\Delta i \to 0}\frac{\Delta\phi}{\Delta i}$$

This quantity is proportional to the slope of the B-H curve of Fig. 1. Thus the incremental inductance of the saturating reactor is also a complicated function, and because the slope changes suddenly at each reversal of current (except at very high flux densities), this function has numerous discontinuities. The maximum and minimum values of the inductive function differ greatly in practical cases, a ratio of many thousand to one being common, while for some high-permeability materials a ratio of the order 40,000:1 is had.

It is interesting to note how this variation of incremental inductance with current influences the shape of the volt-ampere curve of a saturating iron core reactor,[3] taken for example, with a sinusoidal applied voltage. A curve of this kind is shown in Fig. 2a, where the effective current is plotted as a function of the effective applied voltage. The impedance, Z defined as

$$Z = \frac{E_{\mathrm{RMS}}}{I_{\mathrm{RMS}}}\ \text{(sinusoidal)},$$

where E_{RMS} and I_{RMS} are respectively the effective value of voltage and current, is shown in Fig. 2b as a function of the sinusoidal applied voltage. For each value of voltage there is an effective inductance (proportional to Z) which is a sort of an averaged value of the incremental inductances throughout a cycle. By referring to the hysteresis loops of Fig. 1, it may be seen that at small magnetizing forces the incremental values of inductance corresponding to the horizontal segment of the loop are important in determining the average, whereas for the loop a the reverse is true; that is, the steep portions of the loop are of predominant importance. For very high magnetizing forces the horizontal, or saturation, values again become marked, resulting in a relatively low effective impedance and inductance. Thus the $Z = f(E)$ curve has a maximum, there being a predominating saturation effect at both very high and very low magnetizing forces.

It should be further stated that that component of the equivalent series resistance of the reactor, which is due to the hysteresis loss of the core, also depends upon current in a similar manner but to a greater degree.

There is much more to be said about the iron core reactor, but from the foregoing it should be clear that for analytical purposes this reactor, considered as a circuit element, is an extremely unobliging device, being non-linear in all respects.

It is not surprising, therefore, that attempts have been made to approximate the magnetic characteristics (or the derivative thereof) by relatively simple analytic forms,[5,6] varying all the way from two straight lines[2] to hyperbolic functions and series expansions.[4] Most of these methods are accurate over a limited region; the complexity of the physical function precludes the possibility of any one of them being both simple and accurate for any great change in the variables.

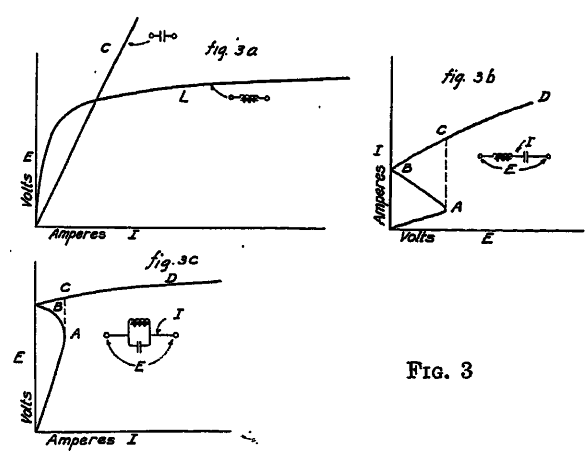

Fig. 3

Properties of Saturating Reactors in Resonance Circuits

Let us consider a reactor for which the effective current is related to the voltage in the manner shown by the curve L of Fig. 3a, which was taken from test data.

2. Boyajian, A., *G. E. Rev.*, vol. 34, 1931, pp. 531 and 745.

3. See discussion, C. G. Suits, A.I.E.E. Transactions, Vol. 50, part 2, 1931.

4. Peterson, *Bell Sys. Tech. Journal*, Oct. 1928, p. 762.

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For purposes of discussion, however, let us consider this reactor to be greatly idealized so that (a) for sinusoidal applied voltage the current is also sinusoidal, and (b) the power losses are zero. These assumptions are impractical but capable of an approximate experimental demonstration.

Fig. 3a includes the curve C which relates the current to the voltage for a capacitance, similarly assumed to be free from losses. Given these two curves of Fig. 3a, and bearing in mind the assumptions involved, one may obtain the volt-ampere characteristic for these circuit elements in series and parallel combination.[7]

In series combination, as shown by Fig. 3b, the current is *identical* in both elements. The difference in the ordinates of the two curves for any value of the abscissa is thus the voltage difference which must be supplied externally. If the current is plotted as a function of this externally applied voltage, the curve of Fig. 3b is obtained. Given these hypothetical circuit elements, the curve which would actually be obtained when they are used in series combination would depend a great deal upon the type of voltage source employed. In particular, it would depend upon the so-called "regulation." For example, if the applied voltage is substantially independent of the current taken by the load, the curve shown by the full line of Fig. 3b could not be obtained, for as soon as the point A is reached (for increasing voltage) the current will suddenly increase to the value at C. The portion B-C-D of the volt-ampere curve will thereafter be traced for any subsequent increase or decrease of voltage, except when the applied voltage decreases to zero, whereupon the current will suddenly drop to zero from the value had at B.

It will be convenient to refer to the value of increasing voltage for which the current suddenly changes to a high value as the *resonant voltage*. Similarly the value of decreasing voltage for which the current suddenly decreases will be called the *dissonant voltage*. It is characteristic of both of the critical voltages that

$$\frac{di}{de} = \infty.$$

A similar situation exists for these hypothetical circuit elements in parallel combination, except that the *role of voltage and current is reversed*. Thus, in Fig. 3c, is shown the curve of voltage E, as a function of current I, similarly obtained from Fig. 3a. For this case the voltage changes suddenly at critical values of current. It will be convenient to refer to these critical values of current, for which the voltage suddenly increases or decreases as the *resonant current* and *dissonant current* respectively, by analogy to the series circuit. It may be seen that in these non-linear resonance circuits there is a similarity between the characteristic of current as a function of the voltage in the series circuit and the voltage as a function of current for the parallel network. That is, if

$$I = f_1(E)$$

is the characteristic of the series circuit, and

$$E = f_2(I)$$

is the characteristic of the parallel circuit, f_1 and f_2 are similar functions.

The series and parallel non-linear circuits discussed above are thus characterized by *voltage sensitivity* and *current sensitivity* respectively, in the sense that for the critical regions a small change in voltage or current will result in a relatively large change in the dependent quantities.

It is possible to specify the properties of the inductive and capacitative elements which are required for $f_1 = f_2$. It is shown in the following paragraphs that for these characteristics to be identical in form it is necessary that the current be related to the voltage in the inductance in the same manner in which the voltage is related to the current in the capacitance. Thus, let i_L, e_L, i_c, and e_c be respectively the currents and voltages in the inductance and capacitance. Then, if

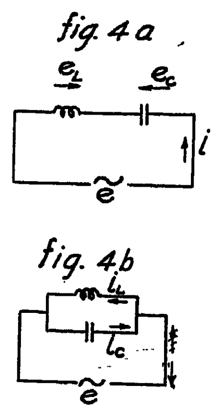

FIG. 4

$$i_L = f(e_L)$$

it is required that

$$e_c = f(i_c)$$

where both of the f-functions are identical.

Thus, consider the inductive and capacitance elements, assumed to be free from power losses, connected in series and parallel combination, as shown in Figs. 4a and 4b. The summation of voltages in the series circuit yields

$$e - e_L + e_c = 0, \tag{1}$$

where e, e_L, and e_c are respectively the instantaneous value of the applied voltage, the inductive voltage, and the capacitance voltage. For the summation of current in the parallel circuit we have:

$$i + i_L - i_c = 0, \tag{2}$$

7. This graphical method was probably first adapted to problems of this nature by Bethenod, *L'Eclairage Electrique*, 1907, p. 289. See also Starke, *Phys. Zeit.*, 18, 1917, p. 6. A comparison of experimental and graphical results is made by H. Gorges, *E.T.Z.*, 39, 1918, p. 101.

where i, i_L, i_c are the instantaneous values of the currents in the branches indicated in the diagram. Let the voltage e_L be related to the current i_L in the inductive element in the following manner:

$$e_L = f_{11}(i_L) \tag{3}$$

where f_{11} may be a linear or a non-linear function. Let the capacitance current i_c be related to the capacitance voltage in the following functional manner:

$$e_c = f_{12}(i_c). \tag{4}$$

Thus (1) becomes

$$e - f_{11}(i) + f_{12}(i) = 0 \tag{5}$$

since $i_c = i_L = i$. A solution of (5) will give the instantaneous value of the current as a function of the instantaneous voltage for the series circuit. From this solution the effective values of current and voltage may presumably be obtained. Let these same inductive and capacitative elements, characterized by (3) and (4), be used in parallel circuit of Fig. 4b. Suppose that (3) and (4) may both be solved for the current as a function of the voltage, and that these solutions are:

$$i_L = f_{21}(e_L) \tag{6}$$

and

$$i_c = f_{22}(e_c) \tag{7}$$

Substitute (6) and (7) in (2) and obtain

$$i + f_{21}(e) - f_{22}(e) = 0 \tag{8}$$

since $e_L = e_c = e$. A solution of (8) will give the instantaneous voltage across the parallel branch as a function of the total current in the series branch, and for this case, as in the above, the effective values of the variables may be obtained. The object is to relate the volt-ampere characteristic of the series circuit to the ampere-volt curve of the parallel circuit, in particular to specify the properties of the functions f_{11}, f_{12}, f_{21}, f_{22} which will cause these characteristics to be identical. Substitute

$$i = e$$

and

$$e = i \tag{9}$$

in equation (5) for the series circuit, and obtain

$$i - f_{11}(e) + f_{12}(e) = 0. \tag{10}$$

Equation (10) will be identical with (8) if

$$f_{11}(\ ) = f_{22}(\ ) \tag{11}$$

and

$$f_{12}(\ ) = f_{21}(\ ). \tag{12}$$

For the *solution* of (10) to be identical with the *solution* of (8) it is sufficient that

$$f_{11}(\ ) = K f_{22}(\ ) \tag{13}$$

and

$$f_{12}(\ ) = K f_{21}(\ ), \tag{14}$$

where K is a constant. If the solutions are identical, the volt-ampere characteristic for the series circuit will be identical to the ampere-volt-characteristic for the parallel circuit. If (13) is true, (14) must be true from the manner of definition. The relation (13) is thus the condition to be satisfied for identical characteristics. From this we may conclude that the voltage of the inductance must depend upon current in the same manner in which the current of the capacitance depends upon voltage.

CORRELATION OF EXPERIMENT AND THEORY

For the purposes of the graphical construction a highly idealized iron core reactor has been assumed. No practical inductance is known which has precisely the properties that have been postulated for the curves of Fig. 3a. It is possible, however, by certain artifices to provide an inductance which for most purposes does have substantially a sinusoidal current for a sinusoidal applied voltage, as well as a non-linear volt-ampere characteristic. This may be accomplished, for example, by the use of an air core (or air gap, iron core) inductance in series with a closed iron core saturating reactor. The maximum effective impedance Z of the saturating element adds to the constant impedance of the linear element to produce a total impedance element which becomes linear for large currents. The departure of the wave form of current from a sinusoid is not marked for any value of current. A volt-ampere curve for a combined inductance of this type is shown as L of Fig. 5. The ratio of the maximum to minimum values of effec-

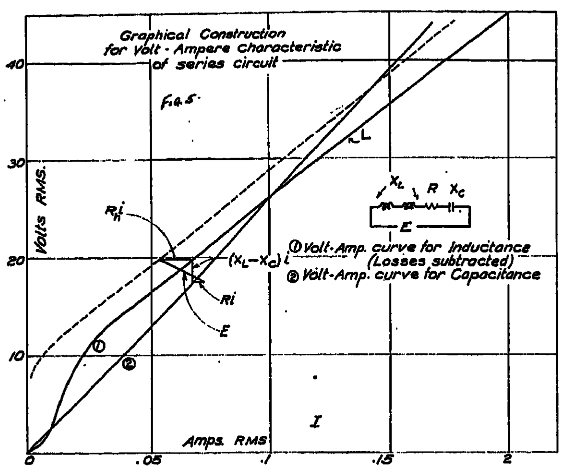

FIG. 5

tive impedance Z may be regarded as an indication of the degree of non-linearity of the element. For the "almost-linear" inductance of Fig. 5 this ratio is 3:1 ($i < 0.5$ ampere), while for a closed iron core reactor of the type used for transformers, a ratio of many hundred to one is had. The important assumption made in the graphical construction for the volt-ampere characteristics of the series and parallel circuits (Figs. 3b and 3c) is that the current is sinusoidal for sinusoidal applied voltage. It may as well be admitted that this is not a very good assumption for a closed iron core reactor for which the incremental inductance experiences a 10,000 times change in a single cycle of alternating current. For this "almost-linear" reactor, however, the change in inductance is relatively small and the current distortion is quite negligible. Fig. 6 shows the volt-ampere curve for the series circuit employing this almost-linear reactor. The full line curve was obtained experimentally while the triangular points were made from the graphi-

cal construction of Fig. 5. It will be noted that the circuit resistance (including that component due to hysteresis and eddy current losses) has been added to the difference in reactive component. This detail of the construction follows from reasons that will be readily apparent. An entirely analogous construction may be made for the parallel circuit, with the result shown in Fig. 7. The close coincidence of the experimentally determined characteristics with the points obtained by the

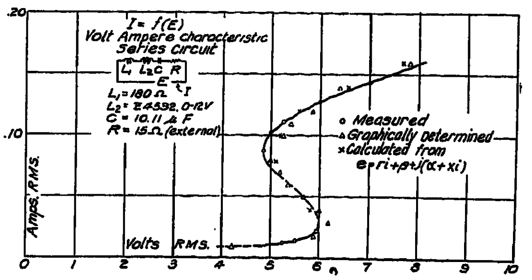

FIG. 6

graphical construction is cited as proof of the essential correctness of the theory of these circuits. It is obviously a great advantage to the analytical theory to deal with an inductive function which does not depart greatly from a straight line. As a result of this simplification, some of the properties of these circuits may be calculated from algebraic forms as simple as those employed for the analogous linear circuits. The points indicated by the crosses of Figs. 6 and 7 were in fact so obtained. It is intended to treat this matter in detail in a separate paper. In practical application of these circuits, some of which are discussed below, it is not always economical to employ an almost-linear type of

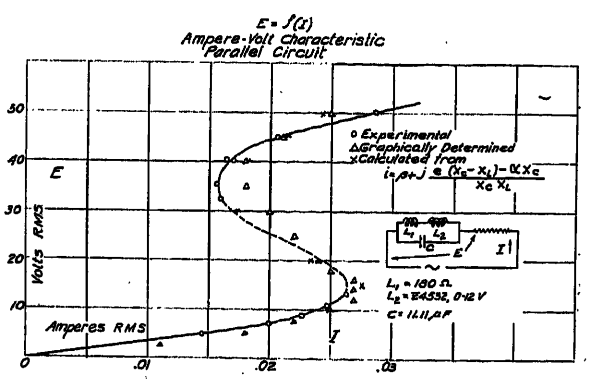

FIG. 7

reactor, whereas in other cases, particularly for current relays, some important advantages result from their use.

VOLTAGE AND CURRENT SENSITIVITY

The characteristics of Figs. 6 and 7 are double valued in voltage and current respectively. Thus, when the series circuit is energized from a source of such characteristics that the voltage is substantially independent of the load, the current suddenly increases at the resonance voltage, for increasing voltage, and subsequently decreases suddenly as the voltage is reduced to the dissonance value. By a number of means, the simplest of which requires an increase in the resistance, the resonance and dissonance voltages may be brought together to produce a single valued volt-ampere characteristic. Curves of this type are shown in Figs. 8a and 8b. An almost linear reactor of the type described above was used in these experiments. The similarity of the volt-ampere curve for the series circuit to the ampere-volt curve for the parallel circuit is quite striking and follows fundamentally from the theorem proved above. The capacitor and reactor characteristics are both similar functions of the opposite variables.

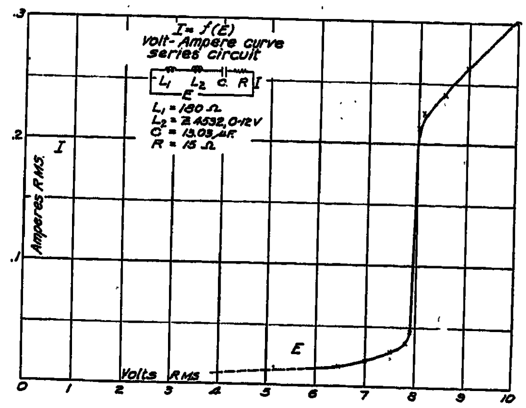

FIG. 8a

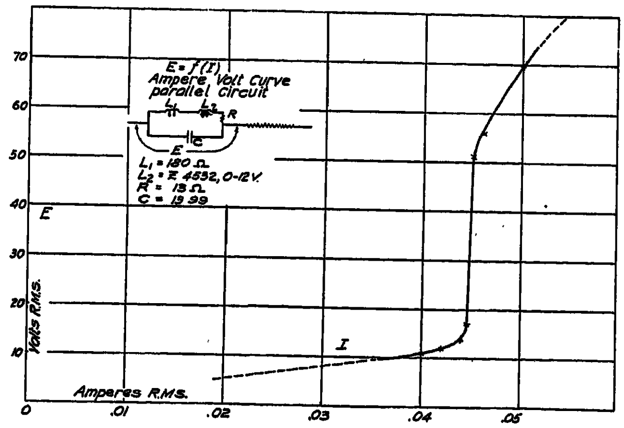

FIG. 8b

One important property of these circuits may be seen from these curves (Figs. 8a and 8b), *i.e.*, the *voltage sensitivity* of the series circuit and the *current sensitivity* of the parallel circuit. Thus, in the critical regions of voltage or current a small change in the independent quantity results in a large change in the dependent quantity.

It is not necessary that the voltage be the independent variable in the series circuit, or that current be the independent variable in the parallel circuit. For example, the series inductance, capacitance, resistance branch may be used in a circuit including a large ballast

resistance so that a large fraction of the voltage supplied by the generator appears across this ballast. The voltage across the resonance branch will vary with current in precisely the manner shown by the curve of Fig. 8a. This application of the circuit is thus adapted to producing a *constant voltage*. In a similar manner the voltage may be made the dependent quantity for the parallel circuit, for which case a *constant current* circuit results.

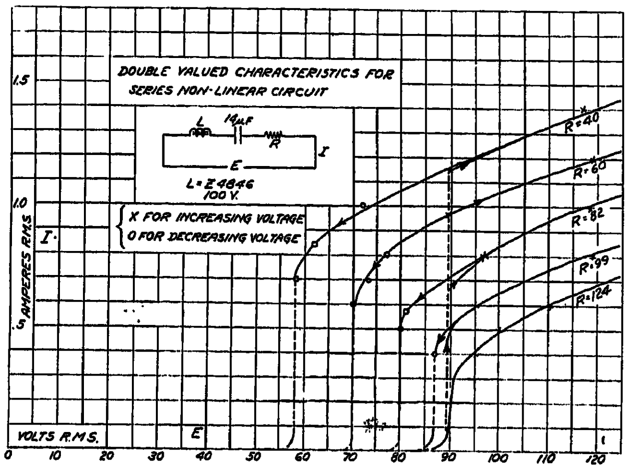

FIG. 9

In summarizing the important properties of these two interesting non-linear circuits it may be stated that the series circuit is adapted to the production of a constant voltage from a variable current, while the parallel circuit is capable of producing a constant current from a changing voltage. The series circuit is further characterized by voltage sensitivity in the sense indicated above, while the parallel circuit is sensitive to current in a like degree. It is the application of these latter two properties, namely, voltage sensitivity and current sensitivity, that will be treated in the subsequent paragraphs.

APPLICATION TO RELAYS

Voltage-sensitive and current-sensitive alternating-current relays are important control elements in a modern electric power system. Their function is usually to determine when voltage control and current control apparatus should operate. They are in many cases required to be as accurate and reproducible in their characteristics as a laboratory voltmeter or ammeter and preferably to cost a fraction as much. The series and parallel non-linear circuits described above have been applied to this problem of sensitive relays.

The fundamental advantages of relays employing resonant circuits follow directly from the large *percentage change in power* at the critical current or voltage. This power may be supplied to a load at an efficiency of the order 30 per cent to 60 per cent in typical cases, at 85 per cent for the best cases. As a result of the large percentage of difference in power which is available, a sensitive relay may be made by controlling a relatively sturdy and economical mechanical element by an electrically accurate circuit. Voltage-sensitive and current-sensitive relays of this general type are treated below.

VOLTAGE RELAYS

The critical change in current that follows from a small change in voltage has been shown in Fig. 8a above. The variation of this characteristic with series resistance R is shown in Fig. 9, which is reproduced from a previous publication.[8] It may be seen that the *resonant voltage* experiences a negligible change when resistance varies, while the *dissonant voltage* changes by a relatively large amount. This property might be inferred from the graphical construction of Fig. 5. It is susceptible to a simple calculation for almost-linear cases. For the present purpose it is sufficient to know that the dissonant voltage varies with R, while the resonant voltage remains substantially constant.

It is found by experiment and may be inferred from the graphical construction that both the resonant voltage and dissonant voltage increase together as the number of turns on the reactor becomes greater.

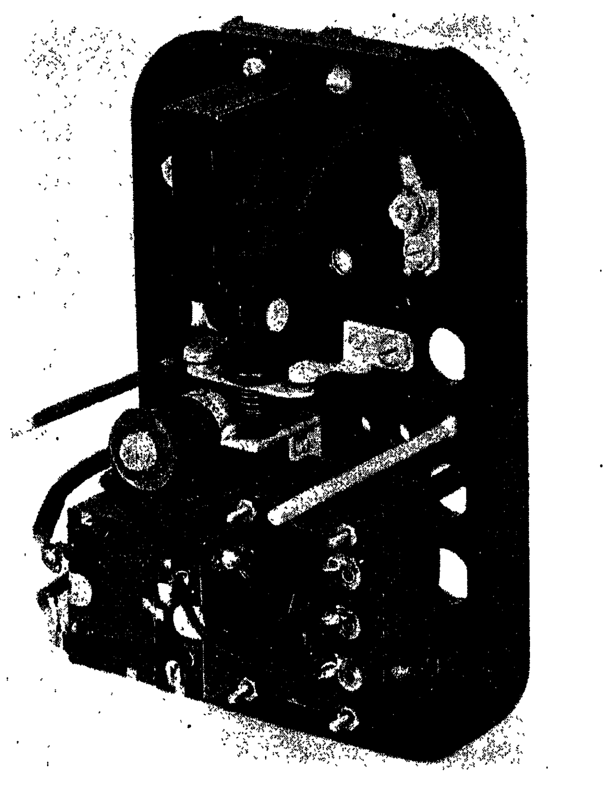

FIG. 10—RESONANT RELAY EMPLOYING NON-LINEAR CIRCUIT

There are a number of optional means of energizing a contactor mechanism from this non-linear series circuit. In addition to the series current varying with voltage in the manner shown by Fig. 8a, the voltage across the resistance varies in a like manner, as well as the effective voltage of the condenser. The inductive voltage drop, however, varies in a much less critical

8. *Physics*, Vol. 1, No. 3, p. 171, Sept. 1931, Fig. 11, p. 178.

manner, since in general a large change in current means a smaller change in flux because of the saturation properties of the iron. For purposes of controlling a contactor mechanism, therefore, power may be taken from the circuit by means of a load (a) in series with the circuit; (b) in parallel with the resistance, (c) in parallel with the capacitance, or (d) in parallel with any two elements. Which of these options is chosen in a practical case depends upon the characteristics of the contactor mechanism and its reaction upon the circuit. When this

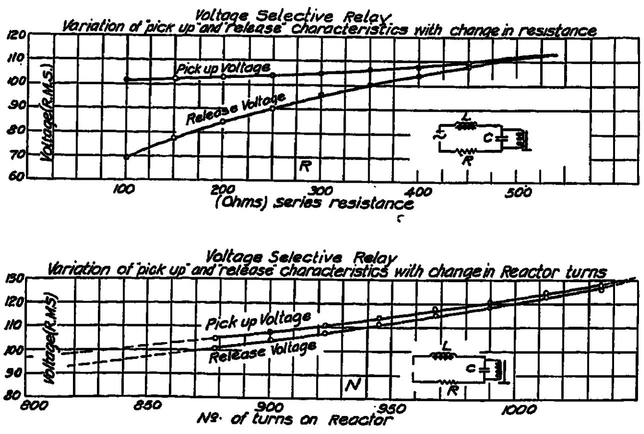

Fig. 11

mechanism is a solenoid and armature (two-position, *not* "floating"), the preferred position in the circuit is in parallel with the capacitance or in parallel with the capacitance and a portion of the inductance. The reasons for this preference will not be discussed in detail here. In Fig. 10 is shown a resonant relay employing a solenoid and armature contactor mechanism energized in parallel with the capacitor of a series non-linear circuit. When used on a source of constant frequency this type of relay may be adjusted to a *minimum* difference between "pick-up" (resonant voltage and "release" (dissonant voltage) of ¼ per cent, and may, by change

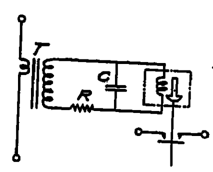

Fig. 12

in resistance alone, be adjusted to a *maximum* difference of 30 per cent referred to the pick-up value. The maximum power requirement is 6 watts at 12 volt-amperes. The dependence of the "pick-up" and "release" characteristics of this relay upon the value of the series resistance and upon the number of turns of the reactor are shown by the curves of Fig. 11. In general, for resonant relays of this type, the adjustments of the percentage difference between the resonant and dissonant voltages is made by a change in resistance, while the voltage region in which they both lie is varied by taps on the windings of the reactor. These adjustments are not strictly independent, but they are found to be sufficiently so for small changes. The reactors used in these relays differ in no important respects from small bell-ringing transformers. Standard transformer steels are employed and conventional tolerances are found to be satisfactory. A relay of this kind is much more economical to build than any previously available device of the same accuracy and the same power-controlling capacity. It should be noted in particular that the high sensitivity of these relays does not depend upon the calibration of a spring or the accurate construction of the mechanical parts, but is fundamentally due to the electrical properties of a circuit which may reasonably be expected to remain constant over long periods of time. The data which are available from life tests and service in the field bear out this conclusion.

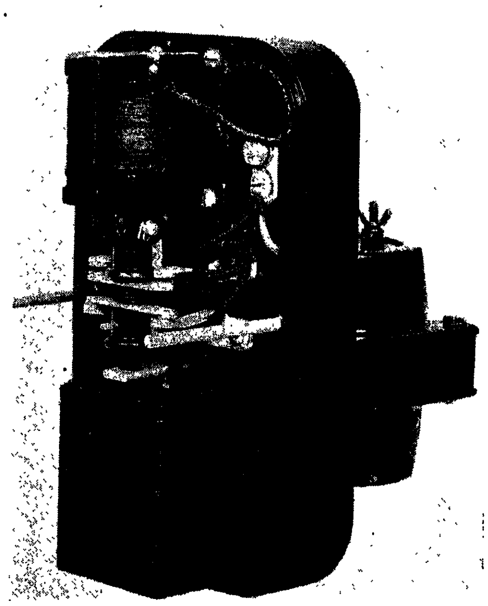

Fig. 13—G-E. Resonant Current Relay

The pick-up and release characteristics of this voltage relay are subject to some variation with frequency. The frequency error is of the order 1 per cent in voltage for a 1 per cent change in frequency. Thus, for use on systems where 0.2 per cent is the frequency variation the change in relay characteristics from this cause alone will be a like order of magnitude.

Current Relays

A resonant voltage relay may be used as a current relay by energizing the former from the voltage drop produced by passing the current through an impedance element. However, the volt-ampere burden of this impedance must be large compared to the volt-ampere requirements of the relay, so that this method is wasteful of apparatus, power, or both. In precisely the same manner in which the series non-linear circuit may be applied to the problem of voltage relays, the parallel

circuit may be used for current relays. The useful property of the circuit for this purpose is shown by the curve of Fig. 8b above, and may be stated to be the great *percentage change* in voltage across the parallel network in response to a small percentage change of current to the parallel branch. This critical change in voltage may be used to energize a contactor mechanism as a load, and this load may be placed (a) in series with the inductance branch, (b) in parallel with the inductance, (c) in parallel with the resistance, or (d) in parallel with the condenser. It may be seen that in general it is required that the voltage across the current relay be a small fraction of the total voltage of the circuit in which it is used. This implies that the microfarad rating of the condenser must be very great for typical cases in which many amperes are to be passed by the relay on 110-volt or 220-volt circuits.

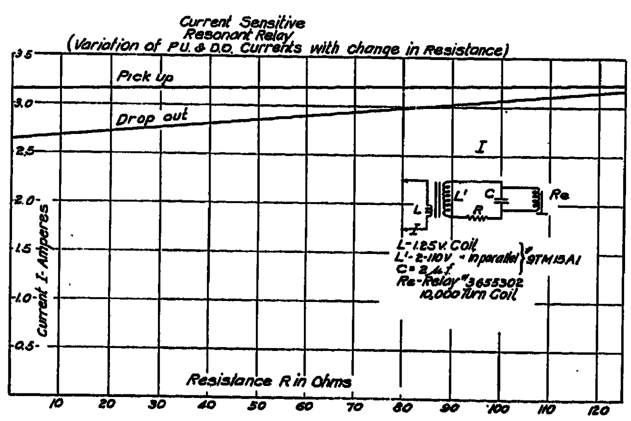

Fig. 14a

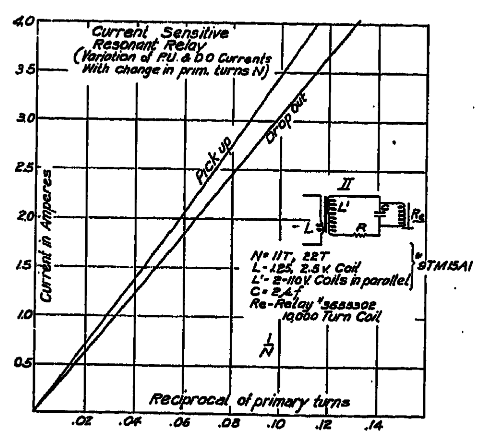

Fig. 14b

In the present state of the art it is uneconomical to build low-voltage, high-microfarad condensers, so that a transformer must be used to perform this transformation. It is feasible, however, to use a winding on the saturating reactor for this purpose, so that no additional equipment is required. The circuit in its practical form is shown in Fig. 12. A relay employing this circuit is shown in Fig. 13. For this particular relay the difference between the resonant current (pick-up) and the dissonant current (release) may be adjusted between limits of 3 per cent and 15 per cent. The resonant current and the dissonant current vary inversely as the number of turns on the transformer T. As in the case of the voltage relay previously discussed, the *percentage difference* between the pick-up and release characteristics, and the *magnitude* of these constants, are thus separately adjustable. These properties are shown by the curves of Figs. 14a and 14b. The total power input at the resonant current is of the order 6 watts at 6.5 volt-amperes.

It may be seen from the curve of Fig. 3c that for this parallel non-linear circuit employing a closed core reactor the voltage across the parallel network increases but little for a relatively large increase in current beyond the resonant value. This means that in practise a current relay which is rated at 5 amperes pick-up will stand a continuous current of a great many times this value. The voltage applied to the condenser and to the contactor mechanism never greatly exceeds the value had at the rated resonant current. The single requirement is that the primary winding of the transformer T (Fig. 12) must be built for whatever maximum current is anticipated. In the case of the relay of Fig. 13, the current may increase to 8 times the pick-up value before the condenser voltage becomes $1\frac{1}{2}$ times the value had at the resonant current. It is relatively simple to provide this margin of safety in the design of these units, so that the problem of under-current relaying is well met with this type of equipment. By the use of a ballast resistance or reactance in series with the current relay an under-voltage relay is produced. This type of relay is capable of tolerating continuous voltages greatly in excess of the actuating voltage.

Discussion

E. S. Lee: In working with these non-linear circuits one is impressed with the consistency of performance which is entirely unlike that which might be expected to anyone familiar with the residual magnetism phenomena encountered in working with direct current, and the erratic behavior of similar circuits which have already been described in recent papers before the Institute by Messrs. Weller, Boyajian, LaPierre and others. From tests made in the laboratory it has been found that the phenomena of rapid increase and decrease in current shown in Fig. 2 of Dr. Suits' paper will repeat itself consistently within one-tenth of a volt when the voltage applied to the circuit is 100 volts.

While some of the characteristics of these circuits have been known for many years, as will be found from the references in the paper, it is only recently that much progress has been made in applying these properties to practical problems. The introduction of non-linear properties opens up a field in which another variable is put at our disposal in producing new and sometimes unexpected results. In the application described in the paper it results in a large increase in current for a small increase in voltage with the series circuit and large increase in current for a small increase in voltage under the proper conditions in the case of the parallel circuit.

Dr. Suits has not pointed out explicitly an essential difference between the series and parallel circuit which is, however, apparent from the curves he has drawn. This is as follows:

When a sine wave of voltage is applied to the series circuit and

the voltage gradually raised the current will follow the volt-ampere curve closely up to the point A, Fig. 3; as the voltage is increased at this point it will be noted that there is no point on this portion of the curve corresponding to higher voltage and we might regard the condition as one of "instability" which results in the current jumping suddenly to the point C as the voltage is increased. With a sine wave of voltage applied to the parallel circuit, however, no such "instability" is encountered as appears evident from the volt-ampere curve. In the case of the parallel circuit, however, by inserting impedance in series with it "unstable" characteristics may be obtained as in the case of the series circuit when a sine wave voltage is applied over all.

The curves shown in the paper refer to the case of an almost linear circuit. In dealing with series circuits which show a large departure from linearity, such as a reactor with closed iron circuit, it has been our experience that the part of the curve up to A, Fig. 3, may be plotted reasonably well by the method given in the paper, *i. e.*, from the volt-ampere curve of the separate elements. The part of the curve from C to D is not so simply obtained. However, by making approximation to allow for the presence of harmonics a fair correspondence with tested values can be obtained. These curves deal only with steady-state conditions and no methods are available for giving the performance under transient conditions. We can also use these curves to show the effect of change of frequency which is to increase the ordinates of the reactor curve and decrease the ordinates of the condenser curve, resulting in a change in the location of the "unstable" portion of the combined volt-ampere characteristic.

From the practical point of view one of the important advantages of these non-linear circuits is that by using them in conjunction with a standard device we can greatly improve its characteristics and reliability within the limits of performance of the non-linear circuit.

A. C. Seletzky: An interesting problem in connection with the non-linear circuit type of relay arises from the presence of harmonic currents or voltages. If we consider, for simplicity the presence of a third harmonic only, the curves shown in Fig. 3 of Dr. Suits' paper undergo the following modifications. The capacity reactance line in Fig. 3a will have one-third the slope of that for the fundamental frequency; the inductive reactance curve will maintain substantially the same shape but its ordinates will be approximately three times greater. The net result is that the intersection of the two curves, which determines the point of resonant or "pick-up" voltage, will occur at a considerably higher value of voltage for the third harmonic than for the fundamental. The resultant volt-ampere characteristic will then be the addition of two curves, such as are shown in Fig. 3b, with the point A for the third harmonic curve occurring at a higher value of voltage. It would be expected, as a result of the foregoing, that the value of "pick-up" and "release" voltages would be affected by the presence of such harmonics because the summation of a number of volt-ampere characteristics for the harmonics would tend to make the resultant characteristic a curve which changes more slowly when the critical voltages are reached. Likewise harmonics would probably affect the value of the minimum difference between "pick-up" and "release" voltages obtainable under sinusoidal conditions. It would be valuable, therefore, when considering the use of this type of relay for close limits, to know quantitatively the effects of harmonics upon the critical voltages and also the effect of phase displacement of the harmonics.

The Coordination of Transformer Insulation with Line Insulation[1]

BY V. M. MONTSINGER[2]
Fellow, A.I.E.E.

and

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Fellow, A.I.E.E.

AT the Toronto Convention of the Institute in June 1930, a paper[4] sponsored by the Transformer Subcommittee of the Electrical Machinery Committee was presented to bring before the membership the status of certain work done by the subcommittee in connection with the coordination of transformer and line insulation.

Two things of outstanding importance were included in this paper: first, a recommended practise of expressing the impulse strength of a transformer in terms of the 60-cycle dry flashover of suspension insulators, and second, recommendations for coordinating the impulse strengths of the transformer and the line insulation. These recommendations included either the use of a safety gap of known flashover characteristics connected in parallel with the transformer, or the reduction of the line insulation to a coordinating value for a distance of one-half mile from the transformer, or a combination of either with a suitable lightning arrester. These recommendations referred to standard line voltages of 69 kv. and above.

Since the publication of this paper the principle of coordination has been widely discussed and it appears to have become generally accepted throughout the industry. While practise has shown that the coordination obtained with one-half mile of standardized line insulation has been satisfactory, there has been a gradual change in favor of the use of an air gap for expressing the impulse strength of transformers and for coordinating purposes. Certain advantages possessed by the air gap have contributed to this change. A gap, for example, can be set at any desired level, while a string of insulators affords no chance for close adjustment. The removal of one disk, for instance, from a string of eight, causes a change of approximately 12½ per cent in the impulse flashover value; the difficulties of adjustment are naturally even more pronounced with shorter strings. Furthermore, the air gap localizes the flashover at a point in the system which can be made convenient for maintenance purposes or for the installation of lightning arresters. Where reduced line insulation corresponding to the original recommendations of the Transformer Subcommittee is being used for one-half mile out from the transformer bank, it is, of course, satisfactory for coordination purposes.

The Transformer Subcommittee has recognized the advantages of the air gap and it is the purpose of this brief progress report to bring to the attention of the Institute membership the following revisions which have been made in the previous recommendations:

1. The yard stick used to express the impulse strength of a transformer has been changed from the 60-cycle flashover value of a given line insulator to a coordinating gap with a given length in inches, as outlined in the following paragraphs and the coordinating principle has been extended to include rated circuit voltages as low as 15 kv.

IMPULSE STRENGTH OF TRANSFORMERS

a. Transformers Receiving Standard Tests as Specified in Paragraph 13-400, A.I.E.E. Standards No. 13

Apparatus conforming with the standards should be so designed that their impulse strength against lightning is greater than the impulse flashover voltage to earth of a coordinating air gap whose spacing[5] is in accordance with Table I.

TABLE I

Rated circuit voltage	Transformer 60-cycle test voltage	Spacing of air-gap
Kv.	Kv. r.m.s.	Inches
15	31	4.25
23	47	6.25
34.5	69	9.25
46	93	12.25
69	139	18.75
92	185	25.00
115	231	31.50
138	277	38.25
161	323	44.50
196	393	54.50
230	461	64.00

b. Transformers Receiving Other Than Standard Test

For transformers receiving a test different from that given for the rated circuit voltage in *a*, the gap spacing

1. Sponsored by the Transformer Subcommittee of the Electrical Machinery Committee, V. M. Montsinger, Chairman, W. H. Cooney, W. M. Dann, H. C. Louis, Basil Lanphier, L. C. Nichols, George Vaughan, F. J. Vogel.

2. Research Engineer, General Elec. Co., Pittsfield, Mass.

3. Asst. Engg. Manager, Westinghouse Elec. & Mfg. Co., Sharon, Pa.

4. *Recommendations on Balancing Transformer and Line Insulations*, V. M. Montsinger and W. M. Dann, A.I.E.E. TRANS., Vol. 49, No. 4, 1930, p. 1478.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

5. Between the ends of two square-cornered, square-cut coaxial rods not more than one-half inch thick up to 69 kv. circuit and not more than three-quarters inch thick for circuits above 69 kv. and so mounted that the rod overhangs its support at least one-half the gap spacing. Also, for circuits above 69 kv. other kinds of air gaps with the recommended spacings such as grading rings on suspension insulators, are satisfactory.

The insulators used as supports should meet the N.E.M.A.-N.E.L.A. 60-cycle flashover requirements for the line voltage.

should correspond to the test which the transformer will receive, in accordance with the relation between test and gap spacing given in *a*.

2. The *Recommendations for Coordinating Transformer Insulation with Line Insulation in the Field*, included in Part II of the Montsinger-Dann paper of June 1930, will be eliminated from the recommendations of the subcommittee. These recommendations involve the three methods of coordinating transformers with line insulation referred to in the opening paragraphs of this report. The coordinating gap referred to in (1) replaces the eliminated recommendations and serves the following purposes:

It establishes the standard of impulse strength required in the design of a transformer.

In practise it limits the magnitude of incoming surge voltages to values less than the impulse strength of the transformer, thereby establishing coordination.

A lightning arrester may be used in conjunction with the coordinating gap to prevent system outages.

Discussion

For discussion of this paper see page 929.

Insulation Coordination of Distribution Transformers

BY E. D. TREANOR*
Associate, A.I.E.E.

and

W. H. COONEY*
Associate, A.I.E.E.

Synopsis.—In this study of insulation coordination of distribution transformers, the operating conditions are reviewed and the requirements of transformers to be operated without protection are outlined. Test results on transformers designed to meet these requirements are given, showing that by the use of shields for the high-voltage windings and thyrite resistors for the low-voltage windings, transformers can be made in which the internal insulation will be protected by flashover of the bushings. The level of insulation chosen and the amount of system protection desired by the use of lightning arresters will determine the economic value of such transformers.

General

Study of Coordination. As an alternative to the use of transformers of present levels of strength with arresters, connected either in the customary manner or interconnected, as suggested at the 1932 A.I.E.E. Winter Convention[6,7] and illustrated in Fig. 6, a study of the idea of coordination of insulation as necessary for the operating conditions of distribution transformers has been carried out and some of the results obtained are reported herein.

During 1924 and 1925, an extensive investigation of transient stress distribution was made on ordinary distribution transformer windings, measurements being made with sphere gaps, and a study of shielded windings was projected. These tests were later checked with the cathode ray oscillograph. In 1929, a number of shielded transformers for transmission line lighting was built and tested, first in the laboratory, and later on a transmission line in Michigan in the summer of 1930. Study of the complete set-up of coordinated distribution transformers involving both mechanical and electrical design has since been carried on, the results on one line forming the basis of this paper.

Operating Conditions. Primary distribution lines are commonly carried on wooden poles with relatively small insulators, the total insulation to ground being uncertain but probably not exceeding 400 kv. impulse. (A rather highly insulated line under actual test would not hold more than 150 kv. impulse.) From the transformer and, frequently, on the same poles run the low-voltage lines terminating in the customer's devices and with the neutral grounded to pipes or, at the least, to other grounds at the transformer or adjacent poles. If of appreciable length, these lines may have an exposure to lightning approaching that of the high-voltage lines. The tank may be grounded, but usually, on the basis of safety to linemen, is isolated. In such cases, the path of an impulse of sufficient magnitude to flash over the insulation of an unprotected transformer is from high-voltage winding to tank to low-voltage winding and thence to ground through the grounded neutral. This means, of course, that lead or major insulation is punctured. That this can and does happen occasionally is attested by records of transformer failures and examination of leads.

Requirements. The requirements in a coordinated distribution transformer, therefore, are that (a) if the tank is grounded, impulses will arc over the bushings of either winding to tank without damage to either bushings or winding, and (b) if the tank is ungrounded, that impulses will flash from one circuit to the tank and thence to the other circuit and ground without damage to windings or bushings. Furthermore, these flashover values should be, at least, of the same order as in present good distribution transformers so that no greater number of flashovers terminating in the secondary neutral will occur than in the case of standard transformers without protection.

The primary winding must be capable of withstanding impulses of any and all magnitudes, polarities, and shapes below the strength of the bushings under the conditions of installation. The secondary winding must be capable, similarly, of withstanding any impulses coming in on the secondary circuit or spilling over abruptly from the high voltage by way of the tank.

If capable of production, such transformers would largely eliminate transformer failures under lightning as a source of trouble. Fuse blowing as a result of flashover would still occur occasionally and arresters would be necessary primarily to prevent outages from this source and from damage to lines and poles. Without them, there would be no limit to the value of transients on lines except the impulse strength of the line structure.

Design. Shields, Windings, and Bushings. Transformers in the 2,400/4,160Y/2,500/4,330Y-volt line are in greatest use and the results presented here are confined to this line. The first step necessarily is to design the high-voltage coil so that its internal insulation, turn to turn, layer to layer, etc., is equal to or higher than the insulation strength to core and tank. A very extensive series of cathode ray oscillograph

*General Electric Company, Pittsfield, Mass.

6, 7. For references see Bibliography.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

studies of internal distribution under different wave forms was made. The initial distribution and oscillations determined by the electrical constants resulting from the physical arrangement of the coils as outlined in the literature on transformers were measured. The application of shields, and design of simple windings which improve the initial distribution and minimize oscillations were then studied. It was found possible to obtain the advantages of the principle of shielding in the particular range referred to, that is, 2,400-volt transformers, 50 kva. and less, with the possibility of extending the practise to other lines.

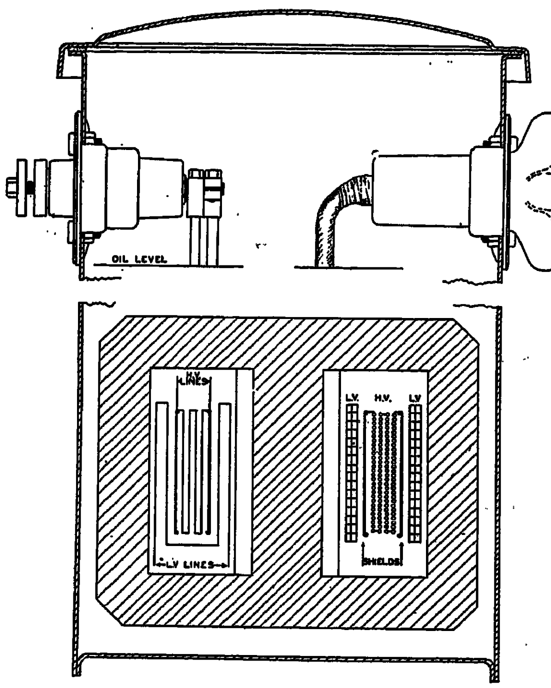

FIG. 1—COORDINATED 2,400-VOLT DISTRIBUTION TRANSFORMER

Shielded high-voltage winding
High-voltage and low-voltage stud bushings

As this class of transformer is operated either between lines, or from line to grounded or ungrounded neutral, the shielding must be effective for either condition without change. Simple cylindrical shields as illustrated in Fig. 1 and a coil consisting of continuous cylindrical layers were found to provide an inexpensive, simple, and effective arrangement which permits the retention of all normal characteristics and, in addition, gives a practically uniform field under transients so that insulation can be applied for known stresses. This is an adaptation of one of the schemes originated by Weed.[3] The design reduces to a straightforward matter capable of proof and with factors of "experience" or guess work eliminated. Starting with a chosen level of strength, we may design the interior of the coil equal to or higher than the major strength to core and tank and protect both by a bushing which will flash over at a predetermined lower strength.

A high-voltage bushing having the best combination of electrical and mechanical features is necessary. For this service, such a bushing should be sturdy and as little likely to suffer mechanical damage in handling as possible. It should be replaceable, and splash-proof. On the other hand, it must have definite electrical characteristics so that all waves regardless of form or polarity which are dangerous to the winding will arc over externally. A tentative design which seems to meet requirements is illustrated in Fig. 1. The live parts can be taped or insulated to prevent contact by linemen, if this is deemed necessary, without affecting the flashover characteristics.

If flashover occurs with an isolated tank, the low-voltage winding is abruptly subjected to a high stress from the core and tank which must be relieved by a flashover from the tank to the low-voltage bushings, preferably the neutral bushing, which may be made slightly smaller to insure this. The low-voltage bushing, also, must be designed with definite arcover strength adapted to protect the low-voltage windings. Bushings having the desired electrical characteristics are shown in Fig. 1.

The low-voltage windings must be protected from a transient internal distribution standpoint primarily against those waves entering from the low-voltage lines in such a manner as to have an appreciable potential difference between lines or between lines and neutral. Due to the usual arrangement of the low-voltage circuit conductors, potential differences between the conductors of very large magnitude are not to be expected, although all conductors may be raised to quite high potentials. This fairly uniform potential to the core and tank is somewhat similar to that due to an impulse entering from the high-voltage side and the insulation must be coordinated with the bushing strength. For potential differences between secondary conductors, effective protection is offered by small thyrite resistors, without gaps, solidly connected between lines and neutral. This adds a small watt loss in the transformer but may be justified in cases of extensive secondary exposure. Small gaps may be used to eliminate this loss at some expense and reduction of reliability.

It seems desirable to point out in this connection also the benefits of another means of accomplishing internal secondary protection, that is, by the use of capacitors connected between lines and neutral. Such use of capacitors in suitable sizes should provide:

a. Protection, by absorbing and reducing the magnitude of secondary circuit impulses.

b. Reduction of lagging magnetizing current.

c. Reduction of radio interference passing through the transformer from external sources.

d. Reduction of the electromagnetically induced impulse in the secondary resulting from a primary circuit impulse.

Testing. Transformers made up along these lines have shown ability to stand up under apparently unlimited

flashovers. This ample strength is believed to be necessary in view of the fact that the ratio of line strength to transformer strength is so high that during the life of a distribution transformer, it may be subjected to a number of waves, approaching or exceeding its strength, which is large compared to the number to which transmission line transformers are subjected. The internal insulation of a small transformer because of the small

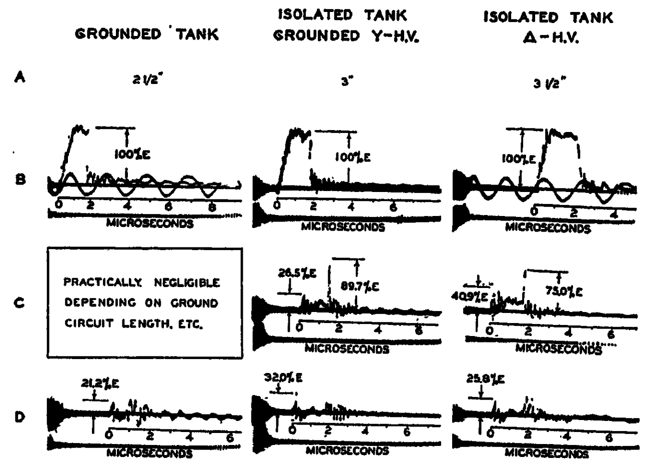

FIG. 2—EFFECT OF OPERATING CONDITIONS ON MAGNITUDE AND DIVISION OF VOLTAGES. TESTS MADE ON A COORDINATED SHIELDED TRANSFORMER RATED H-60-10-2,400-120/240

A —Voltage to cause high-voltage bushing flashover in equivalent rod gap* setting
B —Wave applied to high-voltage winding. Line to ground
C —Tank voltage to ground in per cent of applied voltage to ground
D —Low-voltage line to ground in per cent of applied voltage to ground
Low-voltage neutral grounded in all cases
*½ diameter squared end rods

voltage per turn or layer may be punctured and repetition of the break may recur repeatedly without external evidence. All proof tests were, therefore, made with the transformer excited at full voltage and with full-load current at unity power factor flowing, so that current would not have to be established throughout the test system in order to produce a normal-frequency follow current in case the transient caused a puncture. On this account also, it was desirable to synchronize the impulse with the peak of the normal frequency wave. With all these precautions, it was necessary to tear down and subject to turn by turn examination many coils before there was assurance that no damage was caused in a long series of tests.

TEST RESULTS

Effect of Operating Conditions. The usual practise of isolating the distribution transformer tank leaves no ground potential point but the secondary neutral and by introducing tank capacitance to ground complicates considerably the capacitance relations between component parts of the transformer. The result is that the voltage required to flash over the high-voltage bushings to tank is affected not only by tank-ground capacitance but also by the connection of the high-voltage winding and the extension of the secondary circuit.

In Fig. 2 are summarized tests on a 10-kva., 2,400-volt transformer. Whereas in this particular case an impulse voltage equivalent to a 2½-in. gap flashes over to the grounded tank, isolation of the latter with the high-voltage winding connected from line to line requires a voltage equivalent to a 3½-in. gap. Grounding one high-voltage line reduces the flashover to 3 in. by holding the tank closer to ground potential through high-voltage winding-tank capacitance.

The oscillograms in Fig. 2 picture the sequence of the arcovers from the high-voltage line to tank and from tank to low-voltage circuit. Preceding the discharge over the primary bushing, the tank potential is raised through electrostatic coupling with the high-voltage winding, which the applied wave has entered. As the first flashover occurs abruptly, the tank potential is raised at a rate often exceeding the front of the initial impulse. The transformer core, metallically connected to the tank, rises likewise in potential, stressing the insulation to low-voltage winding, until flashover from the tank to the low-voltage circuit relieves this condition.

The flashover of the high-voltage bushing does not bring the isolated tank up to the full potential of the applied wave due in some degree to the capacity relations to the other windings, to energy losses in the arc, and to the beginning of low-voltage bushing flashover.

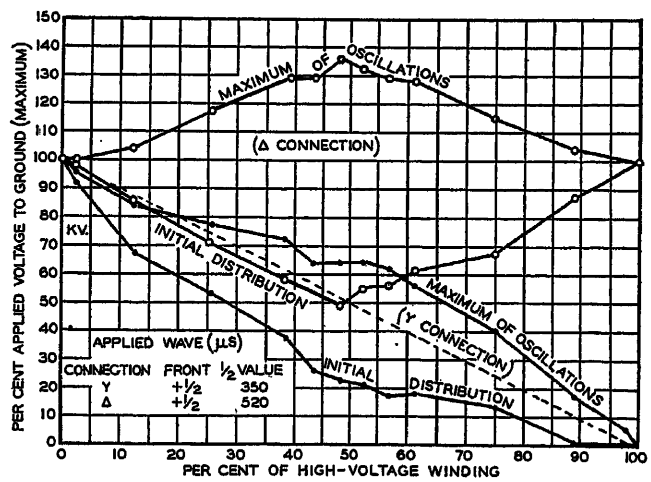

FIG. 3—STUDY OF TRANSIENT VOLTAGE DISTRIBUTION IN UNSHIELDED HIGH-VOLTAGE WINDING OF TRANSFORMER RATED H-60-1½-2,400-120/240

In the oscillograms of secondary line potential to ground may be observed the first sudden rise caused by the impact of the incoming wave on the high-voltage winding transferred through the coupling between windings. This voltage quickly decays through the winding to the grounded neutral. The next sudden rise is due to the flashover of the high-voltage bushing and simultaneous rise of tank potential. This voltage is dissipated by the secondary bushing flashover, as well as through the winding to the neutral.

Internal Impulse Voltage Distribution High-Voltage Windings. Tests are presented in Fig. 3 on a type of distribution transformer which has been in extensive use. With the high-voltage winding in Y connection, the initial distribution and maximum of oscillating voltages are not unlike those already published for larger transformers.[1,3,4] Since distribution transformers for circuits below 8,700 volts are designed to operate in either Y or delta connection, the distribution of impulse

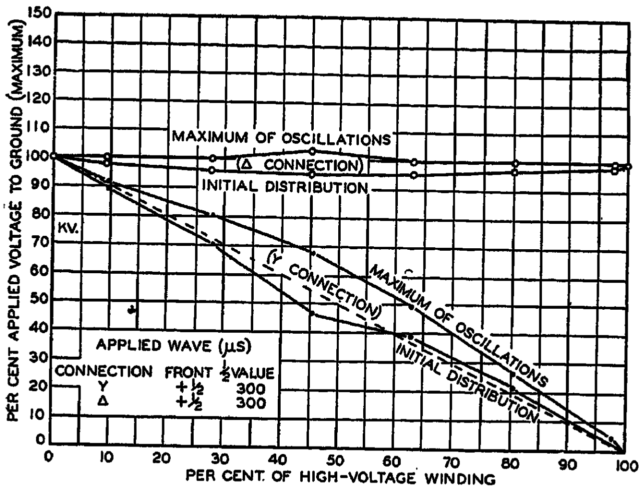

FIG. 4—STUDY OF TRANSIENT VOLTAGE DISTRIBUTION IN SHIELDED HIGH-VOLTAGE WINDING OF TRANSFORMER RATED H-60-1½-2,400-120/240

voltage under the latter condition is of more than academic interest. Curves of the distribution with delta connection are also plotted in Fig. 3.

The specially designed windings with cylindrical shields, previously described, and illustrated in Fig. 1, were subjected to a similar investigation. The voltage distributions on Y and on delta connections, as presented in Fig. 4, show but little divergence from the desired uniform line.

Effect of Shape and Polarity of Impulse. In the tests on the unshielded design of transformer, both the fronts and the tails (duration from crest to one-half crest voltage) of the applied waves were varied through a wide range. As predicted by laws already established, the steeper the front, the more uneven the initial distribution; and the longer the tail, up to one-half the natural period of the transformer, the greater the maximum oscillations. Lengthening of tail beyond one-half the natural period increases the magnitude of oscillations in diminishing degree. The waves applied were gradually shortened in front and lengthened in tail, with corresponding increase in severity of distribution, until the maximum of oscillations under the conditions of Fig. 3 were attained.

In the case of the shielded windings, change of wave shape causes no measurable variation in results because the initial distribution under all conditions is very close to the final one and oscillations are practically eliminated.

Investigation of polarity by impressing negative, as well as positive waves on both types of designs indicated no measurable difference for this class of apparatus, so far as distribution is concerned.

Internal Impulse Voltage Distribution Low-Voltage Windings. Recently, attention has been drawn to the voltage concentrations which may be induced electrostatically and electromagnetically in low-voltage windings during the subjection of the high-voltage winding to impulses.[5] To study this phase in distribution transformers, taps were provided in the 120/240-volt windings of a 1½-kva. shielded high-voltage transformer and impulses applied to the high-voltage winding. Study of the results in Fig. 5 leads to some interesting observations:

a. No serious concentrations are shown.

b. Grounding the low-voltage midpoint results in the interesting condition of the respective line leads rising to equal moderate potentials of opposite polarity above and below the neutral. This distribution of voltages indicates that the predominant factors are oscillation of the winding as a whole superimposed on the voltage induced electromagnetically.

c. The connection of a load or of additional circuit to the low-voltage terminals reduces the voltage to ground at all points under all conditions to a more uniform value.

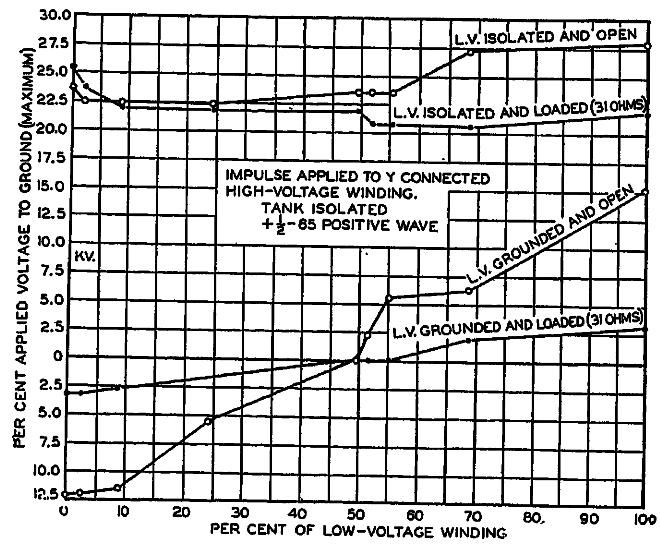

FIG. 5—STUDY OF TRANSIENT VOLTAGE DISTRIBUTION IN LOW-VOLTAGE WINDING (HIGH-VOLTAGE WINDING SHIELDED) OF TRANSFORMER RATED H-60-1½-2,400-120/240 TANK ISOLATED

Impulse Arcover Tests. Coordinated distribution transformers with shielded high-voltage windings were subjected to a series of impulse voltages under various combinations of the following conditions:

Connections:

a. High-voltage lines isolated.

b. One high-voltage line grounded.

c. With 60-cycle operating voltage, impulse synchronized at crest.

d. With rated load at unity power factor on secondary to provide follow current regardless of circuit inertia, should a break in insulation occur.

Tank:

a. Grounded.

b. Isolated.

Impulse:

a. Polarity: positive and negative.

b. Magnitude: adjusted to arc over high-voltage bushing about one-half the time, thus impressing both full and chopped waves on the transformer.

c. Shape: steep front to obtain most severe initial distribution; long tail to develop maximum of oscillations.

The resistance to repeated impulses under any combination of the above conditions was found to be highly satisfactory.

Fig. 6

Discussion

The transformers described have been built for what seems at present the desirable level of strength, that is, on the assumption that a two-in. rod gap for 4,330 Y-volts provides a logical extension of the already agreed upon coordination curve when extended to circuits below 5 kv., and the further assumption that approximately one inch is a proper level for the low-voltage bushings. These bushings must first be corrected for the effects of wave polarity, and the increase in internal stress upon the windings due to the series arcover in the case of the isolated tank must be factored. With these matters properly considered, it appears possible to build transformers at any desired level which will stand up indefinitely under waves which will flash over to the low-voltage circuit. Whether there is economic justification for the development remains to be seen as the level of coordination chosen will determine the cost of the transformer and, consequently, the balance between coordinated transformer and present type plus arrester protection. As the latter seems essential from a general service standpoint, the coordinated transformer may be of value only for marginal cases where the benefits of the arrester must be sacrificed.

Whatever considerations apply to the discharge of impulses into the secondary circuit must be taken into account, with the knowledge that such transformers have a maintained level of strength which will minimize these discharges. As distribution transformers coordinated at the level of line insulation would be prohibitively expensive, a compromise based on sound past practise as outlined above seems to present a logical improvement, largely eliminating transformer failures under lightning and leaving a further degree of perfection to be obtained by the addition of such protective devices as prove necessary.

Acknowledgment

The authors are indebted for assistance to the following members of the Distribution Transformer engineering department: Messrs. M. F. Beavers, L. V. Bewley, M. Broverman, and in particular to Mr. H. C. Stewart, under whose general direction tests were conducted and data correlated. They also acknowledge the excellent testing work of the Pittsfield Works Laboratory, especially that of Messrs. K. D. Beardsley, D. C. Morgan, and L. O. Hubbard.

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Discussion

THE COORDINATION OF TRANSFORMER INSULATION WITH LINE INSULATION

(Montsinger and Dann)

INSULATION COORDINATION OF DISTRIBUTION TRANSFORMERS

(Treanor and Cooney)

C. Francis Harding: With regard to the spark gaps proposed in both of these papers it should be noted that while such gaps "between the ends of two square-cornered, square-cut, coaxial rods not more than one-half inch thick . . . and so mounted that the rod overhangs its support at least one-half the gap spacing" may

be suitable for a parallel discharge gap for the protection of transformers when installed, it is of questionable value as a laboratory testing standard as proposed. The standard sphere gap, already established by the Institute, has the advantage of no time lag and is relatively reproducible for either steep-wave-front surges or 60-cycle potential measurements, (particularly if provided with ultra-violet light). The latter gap has been found to provide an accuracy of from two to three per cent whereas the small sphere gaps operating with no ultra-violet light or those between plane surface electrodes with sharp edges vary as much as 15 to 20 per cent. Unless specified much more in detail than at present therefore such plane surface gaps should not be permitted to be used as a primary standard of high potential measurement, particularly upon steep front transient waves.

Furthermore, it should be clearly recognized by the purchasers of such surge-proof transformers that with the spark gaps or lightning arresters in parallel with the transformers it is the spark gap or lightning arrester which is being tested and not the transformer insulation. Unless additional tests are prescribed without the use of gaps, the real insulation strength and the ratio of insulation strength to gap potential will not be known and may have any value whatsoever above that of the gap. The latter potential, as previously pointed out, is none too definite nor is it easily reproduced as a reference standard.

Referring, in the paper by Messrs. Treanor and Cooney, to the proposed use of resistors between the secondary phase leads and the grounded neutral it should be noted that the possibility of thus relieving, by an amount of 60 to 70 per cent, the transient surge stresses induced upon the secondary was demonstrated in the paper* presented by Mr. C. S. Sprague and the writer at the Winter Convention in January, 1932.

The use of capacitance was also tried in these tests but in both cases the relief was only of local value, *i. e.*, it was only effective very near the point of connection of the resistance load or capacitance. In the latter case, the capacitance, to be sufficiently effective at the low secondary potentials, was considered to be excessively large and too expensive for general application, while the loss in a suitable resistance thus connected may prove a prohibitive expense.

However, with the more and more unsatisfactory lagging power factors recently being found upon transformers in residential distribution systems due to consumers' appliances and with the additional possibility of neutralization of the objectionable effects of lagging magnetizing currents it may be desirable, in the near future, to consider such capacitance connections, possibly for the sake of greater economy upon the primary side of distribution transformers, for the purpose of providing this three-fold advantage, (1) reduction of the magnitude of secondary induced surges, (2) improvement of low lagging power factor due to consumers' appliances, (3) neutralization of the low power factor of the magnetizing current of the transformer especially in cases where the all day efficiency is low.

J. K. Hodnette: Messrs. Treanor and Cooney present a very interesting discussion of the pertinent question of the impulse characteristics of distribution transformers in their analysis of insulation coordination of distribution transformers. In reading the paper, however, I was somewhat confused by the introduction of the question of shielding the high-voltage winding. Although the authors do not definitely state so, one gets the impression that the use of shields and the special arrangement of the high-voltage winding in single coil is necessary for obtaining coordinated insulation. In this connection it is interesting to note that a reasonably good distribution of surge voltage was obtained with an ordinary commercial distribution transformer as shown in Fig. 3 of the paper even with the unusually long test waves of 350 and 520 microseconds length. It is the usual practise to construct distribution transformers with the high-voltage winding divided into two or more parts or sections for the purpose of decreasing the voltage stress across the coils. If the transformers in question were designed with two sections, the initial voltage stress across the coil would be reduced from 100 to 77 per cent as compared to the coordinated design, and with four sections the stress would be reduced from 100 to 46 per cent. It appears from this material reduction in stress that the shields are not essential for building a transformer with coordinated insulation and that it could be accomplished without departing from the practises followed in the past simply by increasing or using more economically the present quantities of insulation if higher than present strength is desired.

The authors have found that transformers with bushings and windings coordinated in the manner described are able to stand up under apparently unlimited flashovers. What were the relative values of bushing flashover and winding insulation breakdown strength in these transformers? Certainly such a transformer could be built which would be self-protecting against surge voltages irrespective of the level of insulation chosen, so that the real problem is one of economics. Such a transformer would have certain definite merits but it has the distinct disadvantage that unless adequately protected by lightning arresters or other protective devices, the bushings will flash over, with the consequent blowing of the primary fuse and service interruption. Protecting the transformer against failure is but one of the major problems involved. Preventing service interruptions as a result of fuse outages is possibly of equal importance as evidenced by the fact that on an average one per cent or less of the transformers in service are broken down each year as a result of lightning, whereas in the neighborhood of 5 to 8 per cent suffer fuse outages. Since the coordinated transformer offers no solution to this serious problem, there is not much to recommend it over the usual type of distribution transformer.

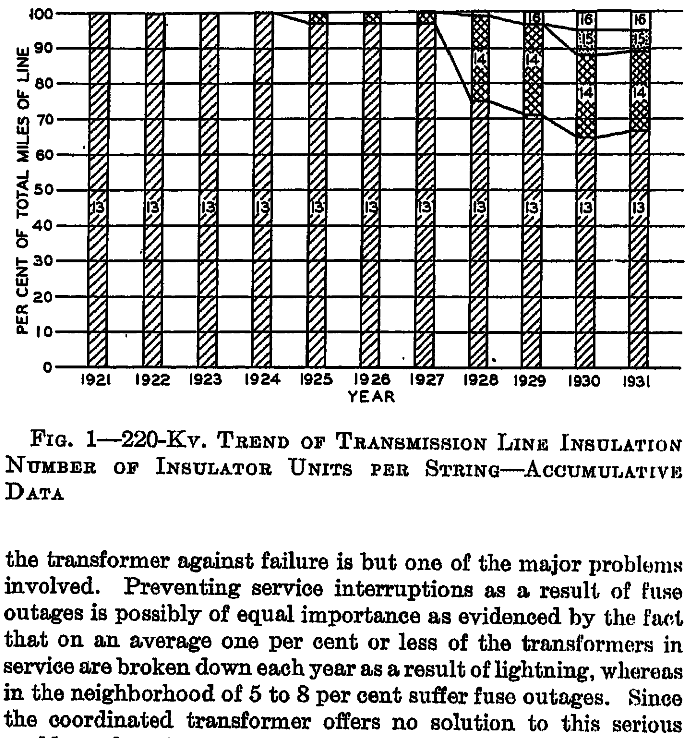

FIG. 1—220-KV. TREND OF TRANSMISSION LINE INSULATION NUMBER OF INSULATOR UNITS PER STRING—ACCUMULATIVE DATA

The whole problem of impulse characteristics of distribution transformers has been carefully investigated by the company with which I am associated during the past several years. Not only were the surge voltage stresses in different parts of the transformer measured by cathode ray oscillographs and sphere gaps, but the ultimate impulse strength of the various parts of the insulating structure determined under conditions simulating those encountered in service with the object of increasing the ability of the transformer to withstand impulse voltages and conditions encountered in service. The result of this analysis was the development of a surge and outage-proof distribution transformer. This transformer was briefly described at the Winter Convention of the A.I.E.E. It is self-contained and self-protecting. The low-voltage insulation is made stronger than the

**Interconnection of Primary Lightning Arrester*, by O. Francis Harding and C. S. Sprague, A.I.E.E. TRANS., March 1932, p. 234.

flashover of the bushings and the high-voltage insulation stronger than the flashover of internally mounted deion protective gaps connected between the primary leads and the tank. The three insulated metallic circuits are so related through the protective devices in this transformer that dangerous voltage stresses cannot exist upon any part of the insulation. The protective gaps, in addition to coordinating the primary insulation, deionize the arc path of the surge. In conjunction with a series resistor they control the magnitude of the follow current and prevent blowing of primary fuses and service interruptions. In a transformer with coordinated insulation, a fuse outage will occur in a majority of cases of bushing flashover.

It is not necessary to flash over both the deion gap and the secondary bushing in order to discharge a surge to ground where

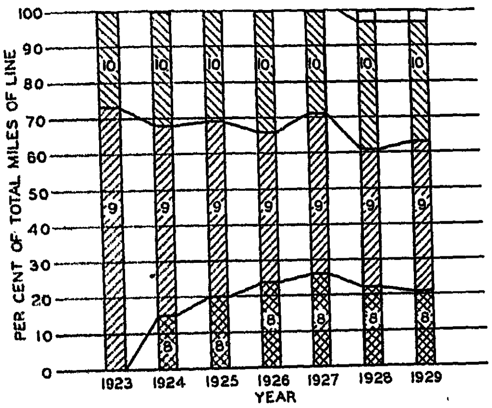

FIG. 2—132-KV. TREND OF TRANSMISSION LINE INSULATION NUMBER OF UNITS PER STRING—ACCUMULATIVE DATA

the tank is insulated from ground. A discharge gap having a flashover voltage much less than that of the low-voltage bushing is connected directly to ground so that surges originating in either circuit are discharged to ground independently of other circuits.

These transformers fulfil the major operating requirements for distribution transformers in a self-contained unit.

1. They are self-protecting against surge voltages.
2. They prevent fuse outages as a result of surge voltages.
3. They introduce no hazard to secondary apparatus, but provide an independent path to ground for surge currents originating in either circuit without involving the other.
4. They are universal in application. They may be operated single-phase or three-phase with tanks grounded or ungrounded.

R. N. Conwell: Messrs. Montsinger and Dann have indicated one of several methods for effecting coordination between transformer and line insulation, namely—the fixing of transformer insulation at a definite, arbitrary value and then relying upon the designer of the transmission line to coordinate with these values. Such a method surely cannot produce a well-balanced, satisfactory, economical system design. The transmission designer is handicapped at the very start by the necessity of meeting limits established without regard to service conditions or local factors such as the character of the terrain, lightning exposure, frequency of storms or the position of the line with regard to storm paths.

The table of protective gap settings given in the paper appears to be predicated on existing transformer design or manufacturing expediency rather than on a consideration of the trends of levels for insulation on lines and in equipment. Table I of this discussion shows the approximate equivalent number of standard insulator units to the air gap spacings given. These may have proved satisfactory for line insulation five or ten years ago but experience, lightning studies which have been recently completed, and demands for better service have all forced a gradual increase in line insulation as shown in Figs. 1, 2 and 3. A similar increase in insulation has been necessary in other voltage classes.

TABLE I

Rated circuit voltage	Transformer 60-cycle test voltage	Spacing of air gap	No. of 5¾-in. units equivalent to air gap spacing
Kv.	Kv. r.m.s.	Inches	(Impulse sparkover)
13.8	28.6	4.25	0.6
23.0	47.0	6.25	1.0
34.5	69.0	9.25	1.5
46.0	93.0	12.25	2.1
69.0	139.0	18.75	3.3
92.0	185.0	25.00	4.6
115.0	231.0	31.50	5.9
138.0	277.0	38.25	7.3
161.0	323.0	44.50	8.6
196.0	393.0	54.50	10.6
230.0	461.0	64.00	12.5

The ultimate purpose of "coordination of insulation" is the improvement of service and the pre-determination of the location of failures. If flashovers can be prevented or made to occur at points where repairs can be made cheaply without interference to service, the criteria has been reached.

The major question involved in the solution of the problem of coordination is whether the insulation of the line or of the equipment, or a compromise between these two, is to be assumed as a base. We are of the opinion that generally line insulation should be taken as the base and insulation at the terminals graded from this value. Other schemes of coordination might be devised, however, depending on the particular bus layout and the relative importance of each piece of equipment. It is conceivable that service conditions may dictate the preferential loss of a bus section rather than a transformer bank. The low values of protective gap settings and transformer insulation eliminate this and other methods of coordination which might profitably be employed.

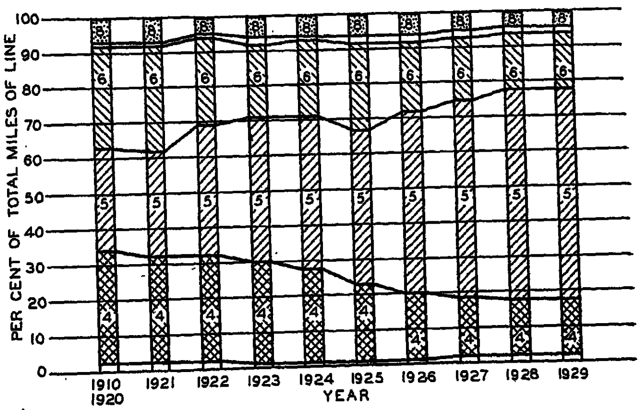

FIG. 3—66-KV. TREND OF TRANSMISSION LINE INSULATION NUMBER OF INSULATOR UNITS PER STRING—ACCUMULATIVE DATA

Merely as illustrative of other methods, Figs. 4 and 5 show the results of an effort to coordinate the insulation of equipment installed at the Roseland Switching Station of the Public Service Electric and Gas Company, with the connecting 132-kv. and 220-kv. lines. Roseland was designed in the winter of 1927-28 at which time very meager information on the surge characteristics of equipment and bushings was available. Complete information is still not available on apparatus bushings or the windings of transformers but the specifications for equipment carried a provision that the bushings should flashover prior to the failure of the windings. In lieu of more authentic data, the curve for the windings of the transformers has been obtained from the curve shown in Fig. 4 of Dr. Fortescue's paper* for needle gaps under

**Rationalization of Station Insulating Structures*, by C. L. Fortescue, A.I.E.E. TRANS., October 1930, p. 1450.

oil using the induced test specifications of the transformer as a basis. Air gaps located in the station were used merely to correct discrepancies in the impulse characteristics of the various types or pieces of equipment.

The plan of coordination proposed by the authors will in most cases necessitate the installation of air gaps of relatively low breakdown value in vulnerable locations in the switch yard which unless protected by lightning arresters, will cause serious interruptions to service. The plan proposed will not meet service requirements generally and therefore the natural result will probably be the construction of a large number of so-called special transformers.

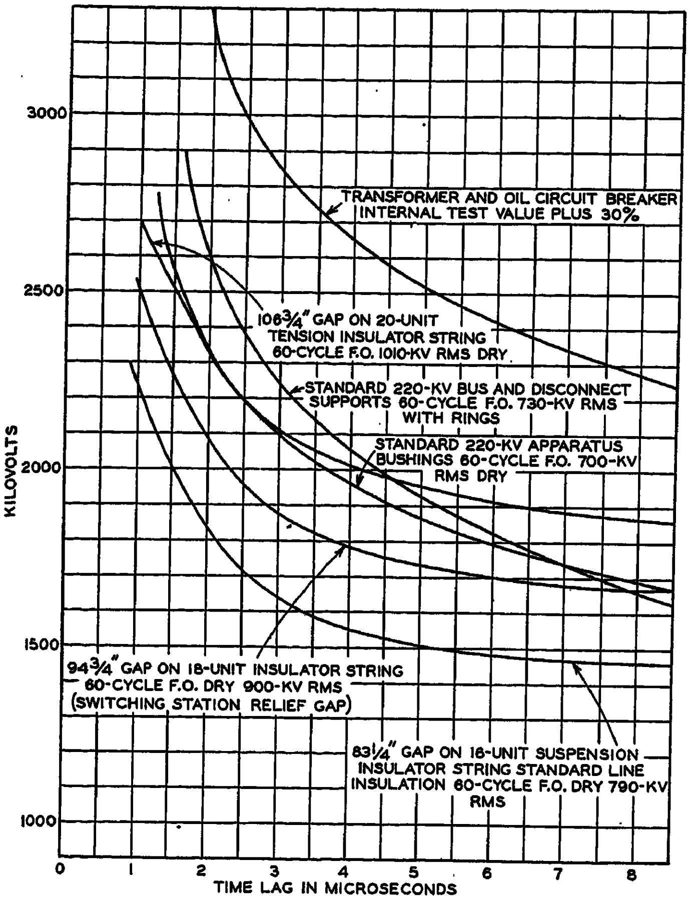

FIG. 4—220-KV. EQUIPMENT

A thorough canvass by a suitable committee of a large number of operating companies to determine preferences on future insulation levels similar to those indicated in Figs. 1, 2, and 3 and methods to be employed in coordination should be made as a basis for the determination of insulation requirements of transformers. Thus a standard may be established which will eliminate the ordering of a large number of specially insulated transformers, allow greater freedom in the design of transmission lines and stations and a better balance in the service and economic features of the system effected.

Philip Sporn: The paper by Messrs. Montsinger and Dann is really nothing but a revision of their paper* presented at the Summer Convention of 1930. The only real differences are: (1) Table I of the original paper has been extended to include recommendations for circuit ratings from 46 kv. down to 13.8 kv.; (2) the other change is in the substitution of a square-cornered, square-cut rod gap for a series of 5¾ in. insulator disks recommended originally.

However, the objections made at that time to the principles of Messrs. Montsinger and Dann, which I stated in a companion paper†, are equally valid today. These principal objections are as follows:

1. *Codification of Insulation Levels.* While the proposed standards do not actually prescribe standard practise, the net effect would be the same as if they did. Not only is the general idea of codifying present practise objectionable, but it is almost impossible to obtain any uniform opinion as to what is a proper standard insulation level; there is on the contrary, a definite and well informed opinion today that no progress will be made in the subject of insulation coordination until the idea of specifying standard practise for any operating voltage is definitely abandoned.

2. There is a very definite lack of knowledge as to the performance of coordinating gaps, regardless of type, when installed in connection with apparatus and under various operating conditions. Our own operating experience, and that of many other companies, definitely and decidedly bear this out. For example, in one case where a 30-in. coordination gap was installed close to a potential transformer and an oil switch, the gap having, according to the best information available, some 20 per cent margin of safety, we had an actual experience that belied the theoretical reasoning behind the setup. Very shortly after the installation

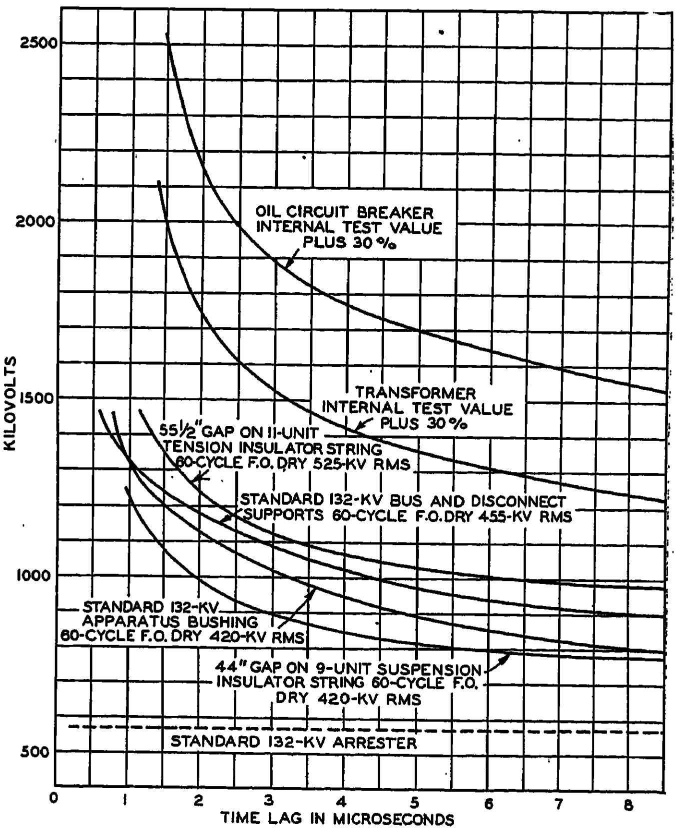

FIG. 5—132-KV. EQUIPMENT

of the gap a lightning storm occurred, during the course of which two bushings failed, one on the transformer and one on the oil switch. The gap not only did not protect the equipment that it was designed to protect, but did not even flash over. The gap has now been set down to 24 in. but there is no definite guarantee that even this size gap will actually coordinate with the terminal equipment.

3. A very definite objection is the fact that this coordination is being carried out in terms of secondary standards. It is high

Recommendations on Balancing Transformer and Line Insulations, A.I.E.E. TRANS., Vol. 49, p. 1478.

†*Rationalization of Transmission Insulation Strength—II*, by Philip Sporn, A.I.E.E. TRANS., 1930, Vol. 49, p. 1470.

time that we started to talk and measure impulse voltage in terms of volts and not in terms of gaps, insulators or some other secondary standard. Our experience in other fields of the lightning problem has shown that no real progress was made until elements of the lightning circuit were expressed in terms of such units as the volt, the ampere, the ohm and the second.

Besides, the whole problem of insulation coordination is much broader than the one envisioned by the authors. Apparently their standpoint aims primarily at insuring a set of operating conditions under all of which, when flashover occurred at a transformer, the transformer would still be safe. However, the problem of coordination is much broader than that, and in its broad aspects involves a much more important problem than one merely of the failure of a particular piece of apparatus. It involves the question of service and the rendering of service of the necessary high standard without going to a setup that involves ruinous expenditures for apparatus either in first cost or in its maintenance. The problem being one of this large scope, it would be far better to get back to fundamentals and to terms that could serve as a basis of reference for all makers of equipment. This means expressing impulse strength in terms of volts and time (although this could, for all practical purposes, be covered by a series of test waves). This would not necessarily preclude the use of gaps under service conditions, but the gaps in themselves would have their strengths and performance expressed in terms of a primary standard and such coordination as required would be done by the designer of the system upon whom the broad problem of system cost and system service has really been thrust for solution. Such a system, too, will very definitely permit the establishment of the fundamental principle of differing insulation levels for the rated or accepted operating voltages. A general discussion of this problem was presented before the Institute some time ago.* The principle has been under discussion now for four years and has been accepted as a workable principle by the joint NELA-NEMA Committee on Insulation Coordination. It does not seem as if the whole problem of coordination would be enhanced by having one group of the industry at the present time advocating coordination for a particular group of equipment at variance with this general principle.

J. B. Hodtum: Messrs. Treanor and Cooney mention that whether there is economic justification for the development of the coordinated distribution transformer described remains to be seen. We would like to point out that the Allis-Chalmers Co. developed a coordinated distribution transformer, known as type SB, which has been on the market for four years and has demonstrated itself satisfactorily from a service point of view and from the economic point of view. We found from experimental impulse tests, which have now been confirmed by four years of service operation, that we could build a coordinated transformer which would flash over the bushings before the transformer itself would fail. We have had over 5,000 of such transformers in service and have yet to learn of a single failure. Numerous cases are known where the bushings flashed over but the transformer did not fail.

We found that satisfactory coordination could be obtained without the necessity or the added complication of installing shields in the windings. If the desired service effect can be obtained without the addition of metal plates in the windings, we consider the transformer a better unit. On the other hand perhaps the use of shields might permit using less insulation than is used with the unshielded transformer, but it seems hardly feasible for 2,400-volt service at least.

We found that in order to obtain the service coordination referred to, that the bushing would not have to take on the peculiar form illustrated in Fig. 1 of the paper, but that on the other hand, the general form of bushing contour which is used with other insulators was entirely satisfactory. Perhaps the shape indicated in Fig. 1 was worked out to simplify the taping of the line conductor where it connects to the bushing. Practically, however, we have found a somewhat larger connection to be necessary, and we have found it desirable to furnish a solderless connector of the clamped type. These connections are often used bare, but where it is desired to cover them we have developed a heavy glass piece which slips over the line lead and makes a very satisfactory protecting cover.

As pointed out in Messrs. Treanor's and Cooney's paper, any coordination of distribution transformer bushing and winding will naturally result in blowing of the fuses when the bushings flash over. To eliminate this effect, lightning arresters or surge diverters of some nature must be furnished whether the transformer is coordinated or not. Surge diverters have been developed which can be applied to Allis-Chalmers stud bushing type transformers mounted either outside or inside of the case. The coordinated design obtained by the use of the stud bushing of proper flashover value with respect to the windings protects the transformer against abnormal voltages. The addition of the surge diverter eliminates fuse outages. This makes a completely satisfactory solution to the distribution transformer insulation problem without complications in the transformer structure itself and one which is right now economically practicable.

F. J. Vogel: The coordination of transformer insulation with the gap is of great value, not only to operating engineers, but to the manufacturer in providing a yardstick to measure the surge strength of station apparatus.

The operating engineer can proportion the station insulation to be above this benchmark, and rest assured that it will be protected. Likewise it provides a benchmark for the designer of station apparatus, and furnishes him an assurance that the design is correct if it is stronger than the specified gap.

It is not essential that the gap be used as the actual protective means in all cases; indeed it is very likely that it will be used merely as the level in the case of very low voltages. For this purpose the table given might be somewhat extended. Values suggested for this are 3 in. for 8,700 volts and 2 in. for 4,300 volts, for outdoor apparatus exposed to lightning.

For indoor apparatus, unexposed to lightning, long experience has shown that the requirements for outdoor apparatus are not necessary. It is suggested that standards for the class of apparatus for unexposed circuits might well be reduced one voltage class, for example to use 3 in. for 13,800 volts instead of 4¼ in. as for exposed apparatus.

Edward Beck: In the coordination of station insulation with definite air gaps for each voltage class, the lightning arrester should limit surge voltages to magnitudes somewhat less than those at which the coordinating gaps will flash over, so that if both gaps and arresters are used in the same station, the arresters will prevent flashover of the gaps and thereby avoid service outages, and if arresters alone are used, they can be depended upon to provide a voltage limiting device as good or better than the coordinating gap.

Lightning protective devices for electrical systems may be said to fall into two general classes. First, those intended for the protection of line insulation against flashover; these may have relatively high operating voltages because the insulation level of the transmission lines is generally high. Second, those intended for the protection of apparatus in stations; these must have relatively low operating voltages in order to coordinate with the gaps proposed for the various voltage classes.

In a discussion of the Lightning Symposium held at the Winter Convention in 1930, published in the TRANSACTIONS OF THE A.I.E.E., July 1930, page 936, the writer proposed that standard lightning arresters be used as a basis for coordination instead of the insulator strings then recommended because the characteristics of the lightning arresters are more uniform and lower than the flashovers of insulated strings such as were proposed for coordination purposes. At the present time, the use of insulator

*_Rationalization of Transmission System Insulation Strength_, by Philip Sporn, A.I.E.E. TRANS., 1928, Vol. 47, p. 998.

strings as a basis for coordination has been discarded and the coordinating medium is a gap in air. The relationship between these coordinating gaps and the lightning arresters holds equally well. A normal autovalve arrester of the same voltage class as the coordinating gap will limit the surge voltages to lower values than the flashover of the gap, as has been determined from numerous laboratory tests that have been made on the lightning arresters and coordinating gaps in parallel, as well as on comparison of data on the impulse flashover of the gaps and the performance of the arresters. Tests have been made for instance, on a lightning arrester of the 230-kv. class in parallel with the 230-kv. coordinating gap. Surges were impressed from the 3,000,000-volt surge generator at the Transformer Works. Similar tests have been made on the same devices of the 138,115, and lower voltage classes. In fact it is the practise in our laboratories at the present time to make all checks of performance of arresters with the recommended coordinating gaps in parallel with the arrester during test.

Comparing the impulse characteristics of the gaps with the performance of autovalve arresters, a typical case, for instance that of the 138-kv. circuit, shows a recommended gap of 38¼ in. with a mininum impulse flashover on a 1½-40 wave of approximately 575-kv. crest.

A 138-kv. class autovalve arrester for use on circuits with the neutral ungrounded or grounded through resistance or reactance would have a maximum permissible line-to-ground rating of 146 kv. This arrester will limit surges to approximately 525-kv. crest, providing a margin between the minimum flashover of the gap on a long wave and the arrester voltage. For surges of greater magnitude rising at the same or steeper rate, the flashover of the coordinating gap would be higher leaving a larger margin between its flashover voltage and the operating voltage of the arrester.

Considering another instance, a 23-kv. circuit, the recommended coordinating gap is 6¼ in. with a minimum impulse flashover on a 1½-40 wave of 120-kv. crest. A normal 23-kv. arrester with a maximum permissible line-to-ground voltage of 25 kv. will limit the surge voltages to between 95- and 100-kv. crest, leaving an ample margin between the flashover of the gap and the operating voltage of the arrester. A similar arrester for use on system with solidly grounded neutral would normally have a maximum permissible line-to-ground voltage rating of 80 per cent or 25 kv. or 20 kv. This arrester would limit the surge voltages to 80-kv. crest, indicating a still greater margin between the coordinating gap and the arrester.

In the coordination proposed in the Montsinger and Dann paper, the arrester falls into its designated place, that of providing a device with an operating voltage below that required to flash over the recommended gaps.

John O. Fenwick: The title of the report by Messrs. Montsinger and Dann indicates that transformer insulation is to be coordinated with line insulation. Therefore, the first logical step for the committee to take would seem to be to determine the insulation levels which operating companies desire to maintain on their lines. With this information at hand, the spacing of coordinating gaps to be used in conjunction with transformers could easily be calculated. It is entirely possible that such a procedure was followed by the committee but the report does not indicate this procedure.

The coordinating gaps used in conjunction with the transformers should be used for operation only and not as a basis of transformer design. Insulation deterioration and the necessity of a factor of safety demand impulse strengths of transformers to be much greater than the flashover value of the coordinating gaps. Operating companies should know and will desire to know the factor of safety that exists in the transformer insulation. Therefore, another set of air-gap spacings should be made standard for impulse testing of transformers, the gap settings taking care of the desired factor of safety.

Such a setup would seem to be most desirable from the standpoint of the operating companies.

C. S. Sprague: The statement is made in the paper by Messrs. Treanor and Cooney that taping the line parts of the bushing does not affect the flashover value. It has been the experience of the writer that such taping does affect the surge flashover; in fact, when determining the surge flashover of transformer bushings, the end having the lower flashover value has often been taped, this forcing the flashover to occur on the other end of the bushing. It would seem that sufficient tape to provide positive protection to the lineman would affect the impulse flashover.

In Fig. 2 the bushing flashover values are given in terms of the equivalent coordinating gap spacing. Also under *B* the time lag of the bushing (or bushings) increases from left to right. Since the coordinating gap itself has some time lag, concerning the extent and variability of which there is not universal knowledge, it seems, at present, that this is an unsatisfactory method of expressing quantitative values. It would be helpful to the reader to know the actual peak values of waves under *B* as well as the spacing of the coordinating gap.

As the authors state, the increased cost of the transformer with coordinated bushings and insulation may not justify its general use. For special locations, however, it seems that proper coordination, in the ratio of 2 or 3 to 1, together with good arrester protection, (which probably implies interconnection) would offer the ultimate in reliability and continuous service.

W. M. Dann: Professor Harding criticizes the use of rod gaps as a laboratory testing standard and recommends the use of sphere gaps on account of their greater accuracy. Granting that the sphere gap is somewhat more accurate it is quite desirable to use a gap with time-lag which a sphere gap does not have. The gap spacings as proposed in this paper are for the purpose of coordinating transformers in the field and not necessarily for testing transformers. Some other kind of gap or different gap settings may be used when the time comes for making impulse tests.

Regarding Mr. Conwell's criticism of the general setup of coordination, like so many others he has assumed that the manufacturers of transformers are attempting to establish the level for the line insulation. This is just the reverse of the intent of these recommendations.

The levels selected merely represent what the data in 1930 showed were the average line insulations used throughout the country. If the average line insulations have increased then it would be logical to increase the transformer insulation levels. Up to the present time we have not seen any concrete evidence that it is necessary to increase these levels which might add an unnecessary burden to the industry as a whole.

It is plainly stated in the paper that where different levels than those selected (for average conditions) are required, the transformer insulation level should be tested and made to fit the requirements. It appears that Mr. Conwell may be influenced by his own company's requirements in advocating that the average level be raised for the whole country. If the majority of operating engineers want the level raised, the manufacturers of transformers will be only too glad to do it, but at an added cost, of course.

We agree entirely with Mr. Sporn that it is almost impossible to obtain any uniform opinion as to what the standard level of insulation should be. It was on this account that we set up certain levels for what appeared to be average line insulation and then stated that for those requiring different levels the gap spacings and transformer test levels should be made to fit these special requirements.

Regarding Mr. Sporn's experience with the two bushings flashing over without the gap going over, a check up on the bushings shows that with the short distance involved (something

like 30 feet) and the large difference mentioned in the flashover levels of the gap and bushings with any of the preferred impulse waves, it would be practically impossible to have this happen unless (a) the gap was improperly installed, or (b) there was a direct stroke on the terminals or bushings.

In connection with his objection to secondary standards, we have used the best available standards. As soon as the various laboratories get their differences ironed out, impulse volts can be used if desired.

The Subcommittee had the choice of either holding up its work until an agreement could be reached on impulse kilovolt flash-over of gaps, disks, etc., or using this so-called secondary standard, which after all is what the man in the field wants to know when installing gaps.

Characteristics of Surge Generators for Transformer Testing

BY P. L. BELLASCHI*
Associate, A.I.E.E.

Synopsis.—The requirements and limitations of surge generators for transformer testing can be summed up as follows:

The voltage that can be obtained is, in the first place, largely determined by the capacity of the surge generator when the capacity of the transformer is great.

If a wave is desired without superimposed oscillations, it is necessary to insert resistance within the generator. The front of the surge then depends upon the inductance of the generator and the capacity of the transformer. This is a matter inherent to all surge generator test circuits. Thus, in general, waves of very steep front cannot be obtained with large transformers.

Further, the inserted resistance also limits the voltage by an amount dependent on the proportion of this resistance to the load resistance.

For transformers of low inductance, the length of the wave obtained is largely determined by the capacity of the surge generator. This results in a requirement of large generator capacity if very long waves are to be produced.

If the lead between the transformer and generator is appreciably long, other oscillations will be set up which are highly damped but are appreciable at the generator end. These oscillations occur on the front of the wave only, and will be prominent when measurements are taken at the surge generator.

INTRODUCTION

IT is the purpose of this paper to consider the characteristics of surge generators in relation to their application to the surge testing of electrical apparatus, particularly transformers. Previously, surge testing has been mostly confined to gaps, insulators, bushings and similar insulation structures. Since the surge testing of transformers has been shown to be desirable,[1] the characteristics of surge generators in testing transformers become of great interest, particularly in the formulation of standards or rules for such testing.

CIRCUITS OF SURGE GENERATOR AND TESTED APPARATUS

The surge generator consists of a bank of condensers or a bank of groups of condensers, each condenser or group charged in parallel to a given potential and all condensers or groups discharged in series through gaps into an external resistance or series of resistors.[2] In the circuit diagram of Fig. 1a, these primary circuit elements are simply represented as a lumped surge generator capacity C_s, charged at potential E, and suddenly discharged through the gap or gaps G into the load or discharge resistance R. An inductance L_s is inevitably entailed in the condenser bank circuit and in leads connecting to the load resistance, also in leads connecting to tested apparatus. Likewise, a resistance R_s is present in the condenser bank circuit, connecting leads, etc., and, for reasons explained below, this resistance is purposely increased and adjusted to have a given proper value. Furthermore, the condenser bank structure and the accessory apparatus of the generator (spheres, leads, insulator strings, etc.) all have capacity to ground. This leakage capacity to ground may, for engineering purposes, be considered as a lumped capacity C_2. Thus, the circuit diagram of Fig. 1b represents in simplified form the equivalent circuit of the surge generator proper.

Apparatus tested, such as bushings, insulators, gaps, etc., are in effect lumped capacity loads. In case the apparatus connects to the generator through a short lead, the diagram of Fig. 1b also represents the equivalent circuit of the generator with load. The capacity C_T is the load capacity; C_L represents the leakage capacity to ground of the generator combined with the load capacity.

Transformers and similar inductive apparatus introduce other elements in the test circuit of the surge generator, with resultant modifications in the surge generated. In the case of transformers with substantially uniform voltage distribution, the equivalent circuit of the transformer consists in effect of a capacity C_T shunted by an inductance L_T. The total load capacity due both to the surge generator and the transformer may be considered lumped in a capacity C_L, as shown in the circuit diagram of Fig. 2. Surge testing is also applied to transformers in which the voltage distribution departs from uniform.[1] The equivalent circuit of these transformers may be represented in simplified

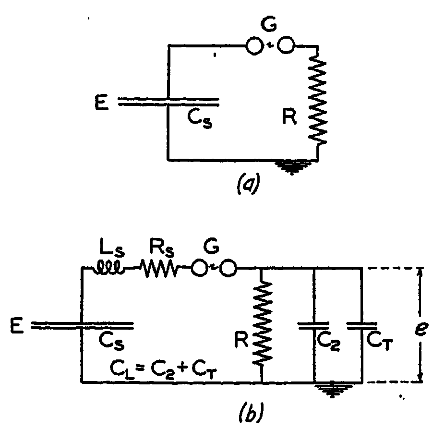

FIG. 1—CIRCUIT DIAGRAM OF SURGE GENERATOR WITHOUT LOAD AND WITH CAPACITY LOAD

*Westinghouse Electric & Mfg. Co., Sharon, Pa.

1. For references see Bibliography.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

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form as shown in Figs. 3 and 4, where the number of meshes depends on the type and construction of the transformer.

The diagram of Fig. 5 gives in a more generalized form the circuit of the generator, the apparatus tested and the intervening lead or other apparatus. Most always a simple lead connects the generator proper to the transformer tested. This connection is made as short as it is physically possible. Whenever there need

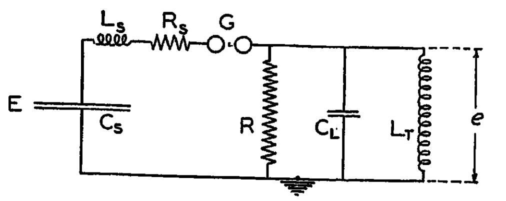


FIG. 2—CIRCUIT DIAGRAM OF SURGE GENERATOR WITH TRANSFORMER LOAD

L_T represents the effective inductance of the winding, taking into account mutual coupling between primary and secondary, and secondary load

be taken account of this additional element, the test circuit may be represented as shown in the diagram of Fig. 6a. For practical purposes this may generally be simplified to Fig. 6b and in turn to Fig. 2.

AMPLITUDE OF SURGE GENERATED—CAPACITY REGULATION

It is desired that surges generated rise smoothly to crest value and decay uniformly to zero value. The surge generator capacity C_s and the load resistance R are both generally large compared to the other elements of the test circuit, so that the self-inductance L_s of the circuit in Figs. 1b and 2 tends to oscillate with the load capacity C_L, unless a proper damping resistance R_s is inserted in the circuit and adjusted to, or is greater than, critical value. The proper value for R_s is approximately

$2\sqrt{\frac{L_s}{C_L}}$, as discussed in Appendixes I and III.

In general, since the load resistance R is much greater than the damping resistance R_s, the maximum surge voltage generated and applied to the apparatus tested depends in a large measure on the total load capacity C_L relative to the surge generator capacity C_s. The capacity regulation of the maximum surge voltage generated may thus be simply expressed as:

$$\frac{e\ (\max)}{E} = \frac{1}{1 + C_L/C_s} \tag{1}$$

Denoting the maximum voltage generated with no load as $e_o(\max)$, then the capacity regulation with load C_T is:

$$\frac{e(\max)}{e_o(\max)} = \frac{1}{1 + C_T/(C_s + C_2)} \cong \frac{1}{1 + C_T/C_s} \tag{2}$$

Thus, in Table I are compared calculated and experimental results on regulation due to the capacity of the transformer tested. The curves in Fig. 7 give the characteristics of the C_s-R-C_L circuit, enabling one to calculate the regulation and to determine the load resistance R required to produce a given length of tail. These curves are calculated from equation (6) in Appendix I.

TABLE I—REGULATION OF SURGE GENERATORS DUE TO CAPACITY LOAD

Transformer load	Surge generated	C_T $\mu\mu$f.	C_s $\mu\mu$f.	Regulation due to capacity of transformer load compared to no-load: Calculated	Experimental
No. 1†	Long tail*	1,200‡	4,200	0.78	0.77
No. 2	Long tail	1,200	12,600	0.91	0.92
No. 3	Long tail	1,100	8,000	0.88	0.89
No. 4	Long tail	3,600	4,200	0.54	0.52

*In the order of and greater than 40 microseconds.
†The transformers tested were all of high inductance.
‡Transformer capacity.

CONTROL OF FRONT AND TAIL OF SURGE—CAPACITY LOAD ON SURGE GENERATOR

As stated before, the series resistance R_s of the surge generator is adjusted to approximately twice the oscillation impedance $\sqrt{\frac{L_s}{C_L}}$, to free the surge generated from superimposed oscillations. For the smooth wave, the series resistance R_s, the load capacity C_L and the circuit inductance L_s determine in a large measure the rise of the front.

The generator capacity C_s, initially at potential E, charges the total load capacity C_L from zero to maximum voltage, C_s corresponding to a large capacity relative to C_L. Neglecting for the moment the circuit inductance L_s, (for large values of load resistance R), the

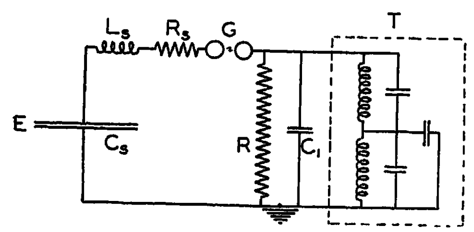


FIG. 3—CIRCUIT DIAGRAM OF SURGE GENERATOR WITH TRANSFORMER LOAD

C_1, load capacity
T, simplified circuit diagram corresponding to a two-group shell type winding (taking into account mutual coupling between primary and secondary)

front of the voltage would rise to 50 per cent crest value in approximately a time 0.693 (R_sC_L) as shown in Fig. 8, curve for $L = O$. (Note: $C_o = C_sC_L/(C_s + C_L) \cong C_L$.) The effect of the circuit inductance on the rise of the front is also shown in Fig. 8, when R_s is adjusted for critical damping. The curves are calculated from equations (7) and (8) in Appendix I. Without damping resistance, the time required for the voltage to rise to the crest of the first oscillation is approximately

$$\pi \sqrt{L_s C_L} = \frac{\pi}{2} (R_s C_L),$$

where R_s is the critical damping resistance.

It should be noted that the inductance L_s and the load capacity C_L are circuit constants inherent in all surge testing circuits and since these constants are not susceptible to appreciable control or modification, it follows that the shortest fronts generated, free from oscillations, are fixed within certain limits. The curves

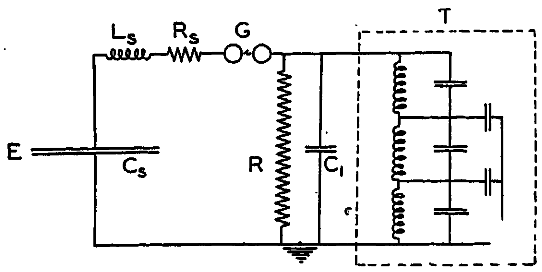


Fig. 4—Circuit Diagram of Surge Generator with Transformer Load

C_l, load capacity
T, simplified circuit diagram corresponding to a three-group shell type winding (taking into account mutual coupling between primary and secondary)

of Fig. 9 give the length or duration of the front as a function of the constants of the surge generator circuit. These curves are calculated from general equation (3) in Appendix I.

A lead connecting the surge generator proper to the apparatus tested introduces the circuit condition as shown in Fig. 6. The stray capacity C_2 of the surge generator proper is generally considerably smaller than the capacity C_T of the apparatus tested. The damping resistance

$$R_s = 2\sqrt{\frac{L_s}{C_L}},$$

where $L_s = L_{s1} + L_{s2}$ and $C_L = C_2 + C_T$, eliminates the low order frequency oscillations superimposed on the front and crest of the surge. High order frequency oscillations of a period approximately

$$2\pi \sqrt{\frac{L_{s1} L_{s2}}{L_{s1} + L_{s2}} C_2}$$

remain superimposed along the rise of the front, and these may be noted on a number of oscillograms. To eliminate these higher-frequency oscillations would require additional damping resistance particularly in the lead, but too large a resistance in the circuit between generator and apparatus tested would be objectionable, as for a given capacity load C_T this tends to lengthen the front. It should be noted, however, that these high frequency oscillations occur only on the front of the surge and they are of short duration; they occur in particular at the surge generator as discussed in Appendix III.

The time duration or length of the tail of the surge voltage to approximately half-crest value depends largely on the value $(0.693 \times RC_s)$; to be more exact, the load capacity also contributes to the tail length, as is shown in Fig. 7. In the case of short tail surges, where R_s becomes appreciably large as compared to R, both resistances affect additively the tail length.

TABLE II—OSCILLOGRAMS AND DATA ON 3,000-KV. SURGE GENERATOR AT SHARON

Oscillogram	Load resistance	Inserted damping resistance*	Nature of load†‡
	(ohms)	(ohms)	(capacity load)
A	8,900	0	No load
B	8,900	100	No load
C	8,900	200	No load
D	8,900	600	No load
E	8,900	0	Capacity load C_T = 700 $\mu\mu$f. approx.
F	8,900	600	Capacity load C_T = 450 $\mu\mu$f. approx.
G	1,850	600	Capacity load C_T = 450 $\mu\mu$f. approx.
H	950	0	No load
I	950	300	No load
J	600	200	No load

*R_s = inserted resistance + inherent resistance of test circuit.
Inherent resistance of test circuit . . . 100 ohms approx.
†Total load capacity = stray capacity to ground of generator + capacity of apparatus tested.
C_L = $C_2 + C_T$, as shown in Fig. 6b.
Stray capacity of generator = ground capacity of condenser bank structure, capacity of sphere gaps, leads, etc . . . 600 $\mu\mu$f. approx.
‡Total inductance = inductance of generator proper + inductance of connecting lead . . . 100 μh approx.
L_s = $L_{s1} + L_{s2}$, as shown in Fig. 6b.
L_{s1} = 60 μh approx.
L_{s2} = 40 μh approx.

In Table II are listed a number of oscillograms corresponding to widely different conditions of capacity loads. Measurements were made at the generator. These experimental results refer to the 3,000,000-volt surge generator at the Sharon Laboratory. Calculations

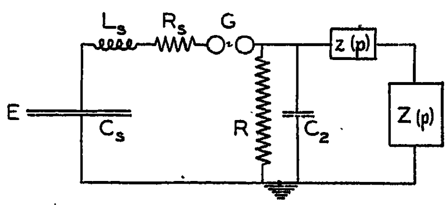


Fig. 5—Circuit Diagram of Surge Generator Connected to Load of Impedance $Z(p)$ Through Impedance $z(p)$

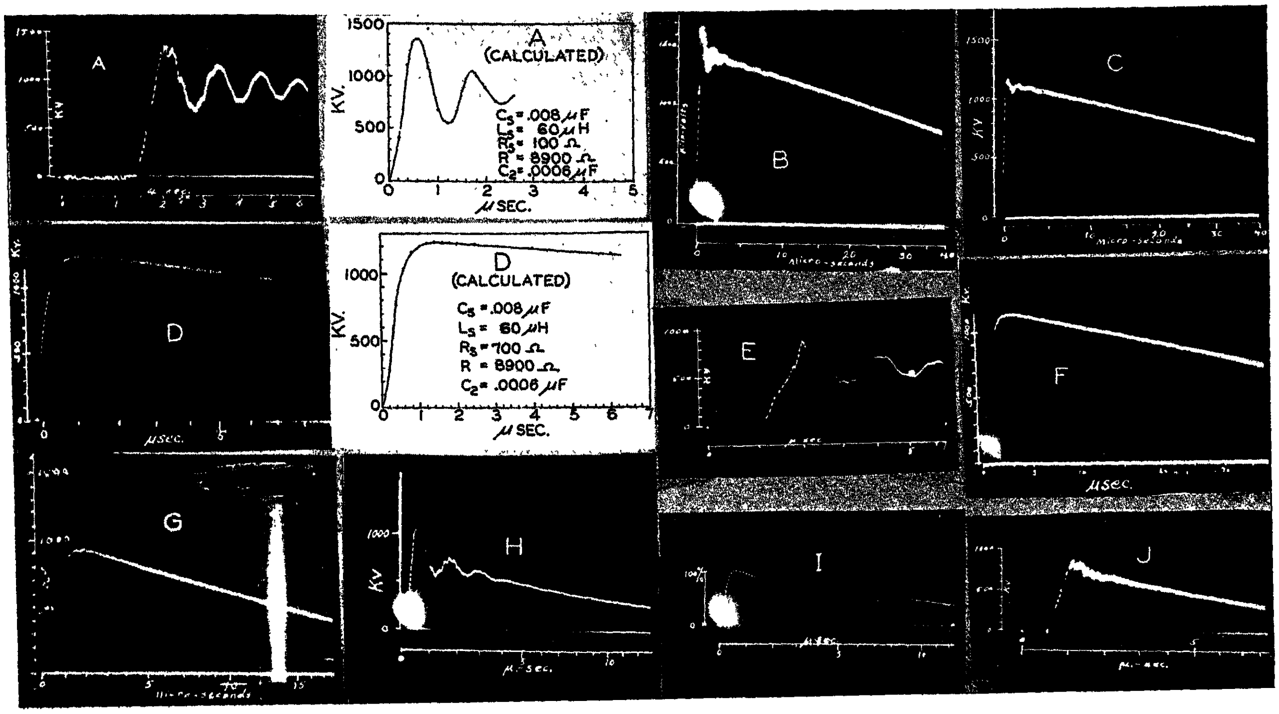
$Z(p)$ is the generalized impedance of the load and represents any type of load, for example a shell or core type transformer load

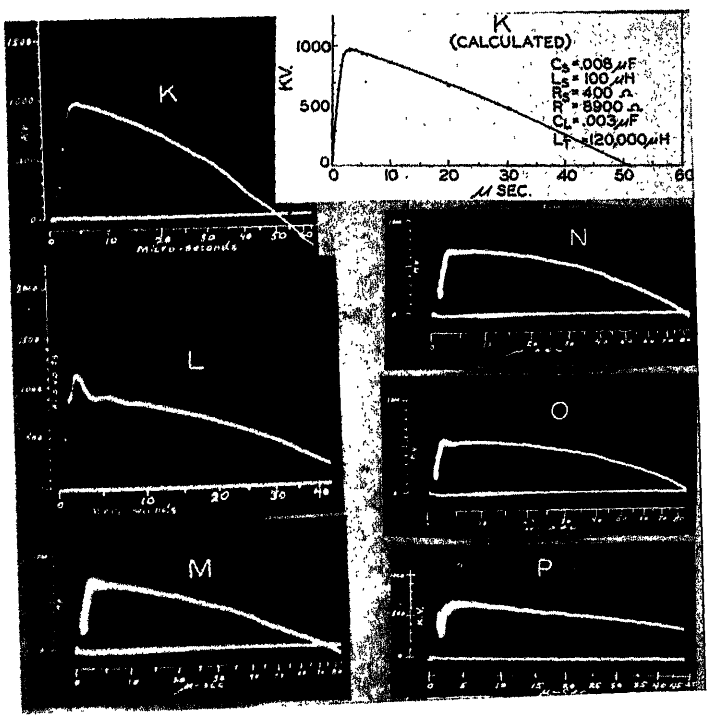
by the methods of this paper of the surge generator performance corresponding to several of the more important oscillograms have been made. The calculated curves corresponding to the oscillograms are included for comparison.

With the surge generator unloaded and with no series resistance added in the condenser bank, the surge voltage generated is given in oscillogram A. The test circuit corresponds to Fig. 6a with no load, however, connected to the surge generator lead. The inherent series

resistance in the condenser bank for oscillogram A is not sufficiently large to dampen the oscillation superimposed on the unidirectional surge. Increasing the series resistance R_s to approximately twice the oscillation impedance $\sqrt{L_{s1}/C_2}$ practically eliminates the oscillation. The inductance L_{s1} and the capacity C_2 are approximately 60 μh and 600 $\mu\mu$f. Oscillograms B, C and D illustrate the point in question.

In the circuit set-up of Fig. 6a, connecting the generator with no damping resistance inserted in the condenser bank to apparatus equivalent to a capacity load C_T = 700 $\mu\mu$f, the surge generated is given by the oscillogram E. The lead connecting from the generator to the capacity load has an inductance L_{s2} in the order of 40 μh. As outlined in Appendix III, the periods of





the superimposed oscillations are given from the relation in equation (13). Thus the calculated fundamental period of oscillation T_1 is 1.93 microseconds which compares closely to the experimental value. The period of the second harmonic T_2 calculates $\frac{1}{3}T_1$. There are also present ripples on the wave which are due to the distributed circuit constants throughout the entire test circuit.

In the circuit set-up for oscillogram F, the load capacity C_T is approximately 450 $\mu\mu$f. A total series resistance R_s = 700 ohms in the condenser bank completely dampens all superimposed oscillations. The surge indicated is practically a 2/55 microsecond wave, or approximately a $3\ R_sC_L/0.693\ R(C_s + C_L)$ wave as determined from curves of Figs. 7 and 9, where $C_L = C_2 + C_T$.

In the surge generator set-up from which oscillogram F was obtained, decreasing the load resistance from 8,900 to 1,850 ohms, R_s = 700 ohms, shortens the tail of the surge to approximately (1,850 + 700)/(8,900) $\times$ 100 per cent $\cong$ 30 per cent. This point is clearly demonstrated in oscillogram G.

Oscillogram H shows the effect on the surge wave resulting from a further reduction of the load resistance from 1,850 to 950 ohms, where R_s = 100 ohms. Increasing the series resistance to R_s = 400 ohms dampens

the superimposed oscillation as shown in oscillogram *I*. Oscillogram *J* corresponds closely to a ½/5 wave.

It should be noted that damping of superimposed oscillations in the equivalent circuits Figs. 1b and 2 may also be secured by a load resistance

$$R \cong \frac{1}{2}\sqrt{\frac{L_s}{C_T}},$$

where R_s may be zero. However, the required damping load resistance would become unduly small in the practical test circuit set-up, so generally damping of oscillations is largely effected by series resistance. The damping resistance at the Sharon Laboratory is distributed along the entire condenser bank.

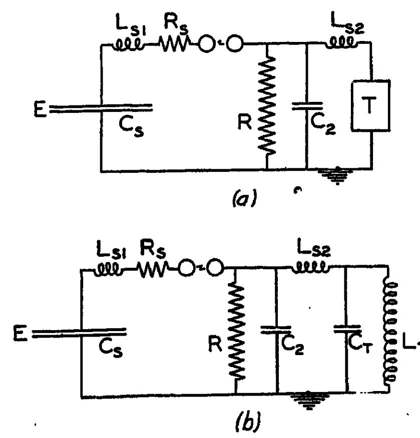


FIG. 6—CIRCUIT DIAGRAM OF SURGE GENERATOR CONNECTED TO TRANSFORMER LOAD THROUGH LEAD OF APPRECIABLE LENGTH

EFFECT OF TRANSFORMER LOAD ON SURGE GENERATED

Transformer loads introduce in various degrees modifying effects on the test circuit. In addition to those modifications on the surge front due to the total load capacity, discussed above, there results from the transformer inductance a modification in the surge tail.

With a transformer load, as shown in Fig. 2, the surge tail depends primarily upon the capacity $C = (C_s + C_L)$, the load resistance R and the transformer inductance L_T in case this circuit constant is relatively small. In Fig. 10 the length of the surge tail is expressed as a function of the test circuit constants that primarily determine the tail. Both the inductance and series resistance of the surge generator have a negligible effect upon the length of long tail waves. It is seen that the transformer inductance plays a major role for values $L_T < 4\,R^2C$, in which case the generator discharges largely through the inductance. In fact for values of L_T in the order of $0.4\,R^2C$, the generator and load capacities oscillate markedly with the transformer inductance, the surge voltage decreasing from crest to half value in a time approximately

$$\frac{1}{2}\sqrt{CL_T}\tan^{-1}\sqrt{\frac{4\,R^2C}{L_T}}.$$

The maximum possible tail length obtainable is with $R = \infty$, for which the tail reaches zero in $\frac{\pi}{2}\sqrt{L_TC}$, and half crest value in $\frac{\pi}{3}\sqrt{L_TC}$. It should be noted that the transformer inductance may become of particular importance in setting a generator test circuit for long tail surges.

Oscillogram *K* shows the effect of a 42,000 kva. surge-proof transformer on the wave of the surge voltage. The capacity and inductance of this transformer are respectively 2,500 $\mu\mu$f. and 0.12 henry; these represent extreme values for transformer units of this size. It is to be noted in oscillogram *K* that the generator and load capacities oscillate with the transformer inductance. The tail of the surge is therefore practically fixed from the generator capacity and the transformer inductance, and the front depends largely on the damping resistance and the total load capacity. The damping resistance R_s is 400 ohms as compared to 200 ohms for oscillogram *L*. This points out again the necessity of adjusting the damping resistance in the order of twice the oscillation impedance $\sqrt{\frac{L_s}{C_L}}$ to eliminate practically all oscillations superimposed on the surge wave. In this case the damping resistance R_s should be in the order of

$$2\sqrt{\frac{100 \times 10^6}{3{,}000}} \cong 360 \text{ ohms}.$$

More accurately, using C_e in place of C_L, the formula

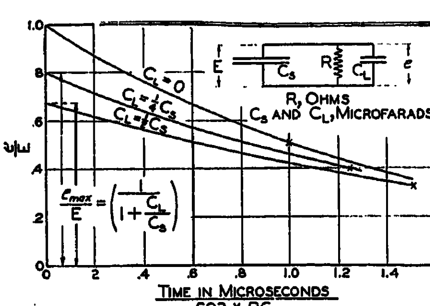


FIG. 7—CHARACTERISTICS OF SURGE GENERATOR CIRCUIT IN RELATION TO CAPACITY REGULATION AND LENGTH OF TAIL OF SURGE GENERATED

Example—Suppose $C_L = \frac{1}{4} C_s$, where $C_s = 0.008\ \mu$f. Find: (a) regulation; (b) value of R to produce a tail of 40 microsec. to half crest value

$$\text{Regulation} = \frac{e \max}{E} = \frac{1}{1 + \frac{C_L}{C_s}} = 0.8$$

Length of tail to half crest value (middle curve) $= 1.25 \times 0.693 \times RC_s$ microseconds

$$R = \frac{40}{1.25 \times 0.693 \times 0.008} \cong 6{,}000 \text{ ohms}$$

gives 430, the difference being due to the large load capacity.

Oscillogram M gives the surge voltage with another large transformer load. With the load resistance removed, the length of the tail is increased to 125 per cent, as shown in oscillogram N. An increase in the generator capacity to 150 per cent further lengthens the tail to $\sqrt{1.5} \times 100$ per cent $=$ 125 per cent, as given in oscillogram O.

Of further interest in regard to the surge testing of transformers is oscillogram P. In this case connecting the transformer produced practically no change in the shape of the surge, except for a lengthening of the front with the transformer connected. The transformer here tested has in the first place a large inductance L_T; second, the voltage distribution is non-uniform and there are marked oscillations in the winding. The oscillations in the winding do not set up any appreciable impedance drop in the generator circuit; that is, the generalized impedance $Z(p)$ of the winding, Fig. 5, is for practical purposes of a high order magnitude relative to the impedance of the surge generator. Surge testing on other transformers with non-uniform voltage distribution have given similar results, thus resulting in a smooth surge wave practically independent of the oscillations in the winding.

The high frequency oscillations due to the lead and the stray capacity of the generator are to be noted along the rising part of the front of the wave on a number of the oscillograms shown.

TABLE III—OSCILLOGRAM AND DATA ON 3,000-KV. SURGE GENERATOR AT SHARON*

Oscillogram	C_s	Load resistance	Inserted damping resistance	Nature of load
	($\mu\mu$F)	(ohms)	(ohms)	(Transf. load)
K	8,000 All condensers in series	8,900	300	42,000-kva. power trans. C_T = 2,500 $\mu\mu$f.; L_T = .12 h
L	8,000 All condensers in series	8,900	100	42,000-kva. power trans. C_T = 2,500 $\mu\mu$f.; L_T = .12 h.
M	8,000 All condensers in series	9,200	300	22,250-kva. power trans.
N	8,000 All condensers in series	Load resistance removed†	300	22,250-kva. power trans.
O	12,000 Two-thirds of condensers in series	Load resistance removed†	300	22,250-kva. power trans.
P	8,000	9,200	700	1,000-kva. power trans.

*Reference to Table II for other test circuit constants.

†Load resistance present is that due to charging buses resistance only. This is very large.

In conclusion, the author desires to acknowledge the helpful assistance of Mr. F. J. Vogel for the experimental data obtained at the Sharon High-Voltage Laboratory, of Mr. H. V. Putman for his constructive criticism, and of other members in the Engineering Department of the Westinghouse Electric and Manufacturing Co.

Appendix I

The solution for the voltage generated in the circuit of Fig. 1b expressed operationally[3] is:

$$e = \frac{\dfrac{R}{RC_Lp + 1}}{\dfrac{1}{C_sp} + L_sp + R_s + \dfrac{R}{RC_Lp + 1}} E$$

$$e = \frac{\dfrac{p}{L_sC_L}}{p^3 + \left(\dfrac{R_s}{L_s} + \dfrac{1}{RC_L}\right)p^2 + \left(\dfrac{1}{L_sC_s} + \dfrac{1}{L_sC_L} + \dfrac{R_s}{L_sC_LR}\right)p + \dfrac{1}{L_sC_sC_LR}} E$$

Expressing the denominator in the form

$$(p + \alpha)\left[(p + \lambda)^2 + \omega^2\right]$$

and denoting

$$A = \frac{1}{L_sC_L},$$

$$e = \frac{Ap}{(p + \alpha)\left[(p + \lambda)^2 + \omega^2\right]} E,$$

which expands into:

$$e = \left[\frac{p}{p + \alpha} - \frac{\lambda - \alpha}{\omega}\,\frac{\omega p}{(p + \lambda)^2 + \omega^2} - \frac{p^2 + \lambda p}{(p + \lambda)^2 + \omega^2}\right]\frac{AE}{(\lambda - \alpha)^2 + \omega^2}$$

Thus the solution of the voltage (e) as a function of time (t) becomes:

$$e = \left[\epsilon^{-\alpha t} - \epsilon^{-\lambda t}\left(\frac{\lambda - \alpha}{\omega}\sin \omega t + \cos \omega t\right)\right]\frac{AE}{(\lambda - \alpha)^2 + \omega^2} \qquad (3)$$

Equation (3) states that an oscillation is superimposed on the unidirectional component $\dfrac{AE}{(\lambda - \alpha)^2 + \omega^2}\,\epsilon^{-\alpha t}$.

The oscillation is completely eliminated for the condition $\omega^2 = o$, in which case equation (3) transforms into:

$$e = \left[\epsilon^{-\alpha t} - \epsilon^{-\lambda t}\left\{(\lambda - \alpha)\,t + 1\right\}\right]\frac{AE}{(\lambda - \alpha)^2} \qquad (4)$$

Whereas, in case ω^2 is negative ($\omega^2 = -\psi^2$), equation (3) transforms into:

$$e = \left[\epsilon^{-\alpha t} - \epsilon^{-\lambda t}\left(\frac{\lambda-\alpha}{\psi}\sinh\psi t + \cosh\psi t\right)\right]\frac{AE}{(\lambda-\alpha)^2-\psi^2} \qquad (5)$$

Referring to the circuit of Fig. 1b, within the practical range of the circuit constants, the circuit elements: C_s, L_s, R_s and C_L constitute for practical purposes the oscillating circuit. As it is desirable to secure a smooth

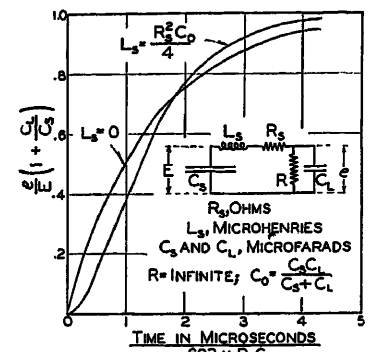


Fig. 8—Effect of Inductance of Surge Generator on Front of Surge

wave of the surge generated, to this end the series resistance is increased for practical purposes to a value in the order of

$$R_s \cong 2\sqrt{\frac{L_s}{C_o}} \cong 2\sqrt{\frac{L_s}{C_L}}; \quad C_o = \frac{C_s C_L}{C_s + C_L} \cong C_L$$

A damping series resistance in this order practically eliminates the superimposed oscillation in equation (3).

Introducing the condition

$$R_s = 2\sqrt{\frac{L_s}{C_o}}$$

in the original operational expression above and expressing the time constants in term of $R_s C_L$, the operational expression becomes:

$$e = \frac{Ap}{p^3 + ap^2 + bp + c}$$

where

$$a = \left(\frac{1}{R_s C_L}\right)\left(4\frac{C_L}{C_o} + \frac{R_s}{R}\right)$$

$$b = \left(\frac{1}{R_s C_L}\right)^2\left(4\frac{C_L}{C_o}\frac{C_L}{C_s} + 4\frac{C_L}{C_o} + 4\frac{C_L}{C_o}\frac{R_s}{R}\right)$$

$$c = \left(\frac{1}{R_s C_L}\right)^3\left(4\frac{C_L}{C_o}\frac{C_L}{C_s}\frac{R_s}{R}\right)$$

$$A = \left(\frac{1}{R_s C_L}\right)^2\left(4\frac{C_L}{C_o}\right)$$

Thus the solution for the voltage (e) is expressed in terms of the time constant $R_s C_L$. The curves in Fig. 9 are calculated in terms of $R_s C_L$ for various ratios of $\frac{C_L}{C_s}$ and $\frac{R_s}{R}$. These curves summarize the characteristics of circuit Fig. 1b, particularly the relation of the time constant $R_s C_L$ as a function of the duration of the surge front.

In case L_s and R_s are small relative to the other circuit constants, the crest and tail of the surge are given for practical purposes by the simple relation:

$$e = \frac{E}{1 + C_L/C_s}\,\epsilon^{-\frac{t}{R(C_s + C_L)}} \qquad (6)$$

The curves in Fig. 7 give the characteristics of this circuit.

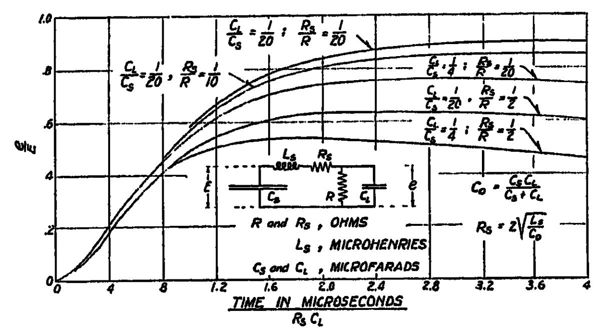


Fig. 9—Characteristics of Surge Generator Circuit in Relation to Front and Crest of Surge Generated

Example—Capacity load, $C_L = 0.002\ \mu f$.

Surge generator constants, $C_s = 0.008\ \mu f$ and $L_s = 100\ \mu h$.

Problem is to find shortest front obtainable with a smooth surge having a 40-microsec. tail

Series damping resistance required,

$$R_s \cong 2\sqrt{\frac{L_s}{C_O}} \cong 2\sqrt{\frac{L_s}{C_L}} \cong 500 \text{ ohms}$$

From curves of Fig. 7 the load resistance required to give 40 microsec. tail is $R \simeq 6{,}000$ ohms

$$\text{Then } \frac{C_L}{C_s} = \frac{0.002}{0.008} = \frac{1}{4}; \frac{R_s}{R} = \frac{500}{6{,}000} = \frac{1}{12}$$

From interpolation of the proper curves of Fig. 9 the time for the surge to reach full crest value is approx. $2.5\, R_s C_L = 1{,}250 \times 0.002 = 2.5$ microsec.

In case the load resistance R is very large and for

$$R_s = 2\sqrt{\frac{L_s}{C_o}},$$

equation (3) becomes:

$$e = \left[1 - \epsilon^{-\frac{R_s t}{2L_s}}\left(\frac{R_s}{2L_s}t + 1\right)\right]\frac{E}{1 + \frac{C_L}{C_s}} \qquad (7)$$

and for zero inductance ($L_s = o$)

$$e = \left[1 - \epsilon^{-\frac{t}{R_s}\left(\frac{1}{C_s} + \frac{1}{C_L}\right)}\right]\frac{E}{1 + \frac{C_L}{C_s}} \qquad (8)$$

The last two equations are plotted in Fig. 8 to compare the rate of rise of the front with and without inductance.

Appendix II

A complete analysis of the circuit in Fig. 2 results in complex expressions. A clearer insight into the practical problem, and with a good degree of accuracy, is best gained by segregating the elements of the circuit that determine respectively the front and the tail of the surge. The front of the surge depends largely, for circuit conditions of practical interest, on the circuit elements discussed in Appendix I. The tail of the surge for large values of L_T relative to 4 R^2C is also given for practical purposes in the equations of Appendix I. In case L_T is considerably less than 4 R^2C, the tail of the surge then depends in a large measure on the elements of the circuit in Fig. 10; the operational solution of this circuit is:

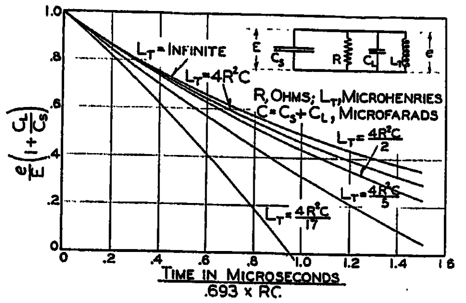


FIG. 10—EFFECT OF TRANSFORMER INDUCTANCE ON TAIL OF SURGE

Example—C_s = 0.008 μf; L_T = 0.12 × 10^6 μh; load capacity C_L = 0.002 μf; L_s and R_s disregarded

Problem: With R = 6,000 ohms, which was required to produce a 40 microsec. tail either without transformer connected or with transformer of high inductance connected, find length of tail with transformer of low inductance connected

$$\frac{L_T}{4R^2C} = \frac{0.12 \times 10^6}{4 \times 36 \times 10^6 \times 0.01} = \frac{1}{12}$$

Reading from the curves we get time for tail to reach half value = 0.57 × 0.693 × RC = 24 microsec.

The maximum possible tail obtainable is with $R = \infty$, for which the tail reaches zero in

$$\frac{2\pi}{4}\sqrt{L_TC} = 1.57\sqrt{0.12 \times 10{,}000} = 55 \text{ microsec.}$$

The slope of the tail under this condition is sinusoidal (see oscillograms N and O), so it reaches half crest value in 2/3 its total length or 37 microsec.

$$e = \frac{\dfrac{RL_Tp}{R + L_Tp}}{\dfrac{1}{Cp} + \dfrac{RL_Tp}{R + L_Tp}} \; \frac{E}{1 + \dfrac{C_L}{C_s}}$$

$$= \frac{p^2}{p^2 + \dfrac{1}{RC}p + \dfrac{1}{L_TC}} \; \frac{E}{1 + \dfrac{C_L}{C_s}}$$

Expressing the denominator in the form $(p + \alpha)^2 + \omega^2$,

$$e = \frac{p^2}{(p + \alpha)^2 + \omega^2} \; \frac{E}{1 + \dfrac{C_L}{C_s}},$$

which expands into:

$$e = \left[\frac{p^2 + \alpha p}{(p + \alpha)^2 + \omega^2} - \frac{\alpha}{\omega} \frac{\omega p}{(p + \alpha)^2 + \omega^2} \right] \frac{E}{1 + \dfrac{C_L}{C_s}}$$

Thus the solution of the voltage e as a function of the time t becomes:

$$e = \epsilon^{-\alpha t} \left[\cos \omega t - \frac{\alpha}{\omega} \sin \omega t \right] \frac{E}{1 + \dfrac{C_L}{C_s}} \qquad (9)$$

where

$$\omega = \sqrt{\frac{1}{L_TC} - \frac{1}{4\,R^2C^2}}; \quad \alpha = \frac{1}{2\,RC}; \quad C = C_s + C_L$$

For the condition $L_T = 4\,R^2C$, equation (9) transforms to:

$$e = \epsilon^{-\alpha t}(1 - \alpha t) \frac{E}{1 + \dfrac{C_L}{C_s}} \qquad (10)$$

These equations are evaluated in the curves of Fig. 10 for various values of L_T that are of practical interest.

Appendix III

The effect of the lead connecting the generator to the apparatus tested is of interest from various aspects.

In case the lead is short relative to the physical outlay of the generator, the equivalent test circuit is for practical purposes as in Fig. 2. In such a case, voltage measurements at the generator are practically identical to measurements at the apparatus. A smooth surge wave is secured by means of an appropriate damping series resistance.

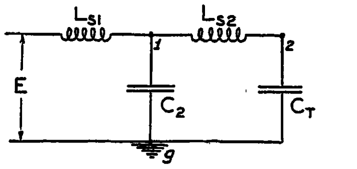


FIG. 11

A lead of appreciable length relative to the inductance of the generator proper introduces a condition in the test circuit as shown in Fig. 6. The solution of these circuits results in complex expressions, hence a physical analysis is considered below resulting in simpler terms and a clearer insight into the problem. With no damping resistance, the equivalent circuit of interest is as

shown in Fig. 11; the operational solution of this circuit is:

$$e_{1g} = \frac{\dfrac{\dfrac{1}{C_2p}\left(L_{s2}p + \dfrac{1}{C_Tp}\right)}{\dfrac{1}{C_2p} + L_{s2}p + \dfrac{1}{C_Tp}}}{L_{s1}p + \dfrac{\dfrac{1}{C_2p}\left(L_{s2}p + \dfrac{1}{C_Tp}\right)}{\dfrac{1}{C_2p} + L_{s2}p + \dfrac{1}{C_Tp}}} E$$

$$e_{1g} = \frac{\dfrac{p^2}{L_{s1}C_2} + \dfrac{1}{L_{s1}L_{s2}C_2C_T}}{p^4 + \left[\dfrac{1}{L_{s2}C_2}\left(1 + \dfrac{C_2}{C_T}\right) + \dfrac{1}{L_{s1}C_2}\right]p^2 + \dfrac{1}{L_{s1}L_{s2}C_2C_T}} E$$

$$e_{1g} = \frac{\dfrac{p^2}{L_{s1}C_2} + \omega_1^2\,\omega_2^2}{(p^2 + \omega_1^2)(p^2 + \omega_2^2)} E.$$

The solution of the voltage (e_{1g}) as a function of time becomes:

$$e_{1g} = \left[1 + \frac{\dfrac{1}{L_{s1}C_2} - \omega_2^2}{\omega_2^2 - \omega_1^2} \cos \omega_1 t + \frac{\omega_1^2 - \dfrac{1}{L_{s1}C_2}}{\omega_2^2 - \omega_1^2} \cos \omega_2 t\right] E \quad (11)$$

In much the same way

$$e_{2g} = \frac{1}{L_{s2}C_Tp^2 + 1} e_{1g}$$

$$e_{2g} = \left[1 - \frac{\omega_2^2}{\omega_2^2 - \omega_1^2} \cos \omega_1 t + \frac{\omega_1^2}{\omega_2^2 - \omega_1^2} \cos \omega_2 t\right] E \quad (12)$$

where in equations (11) and (12)

$$p^4 + \left[\frac{1}{L_{s2}C_2}\left(1 + \frac{C_2}{C_T}\right) + \frac{1}{L_{s1}C_2}\right]p^2 + \frac{1}{L_{s1}L_{s2}C_2C_T} = (p^2 + \omega_1^2)(p^2 + \omega_2^2)$$

$$= \left[p^2 + \left(\frac{2\pi}{T_1}\right)^2\right]\left[p^2 + \left(\frac{2\pi}{T_2}\right)^2\right] \quad (13)$$

Thus for the circuit conditions:

Example 1: $L_{s1} = 60\ \mu h$ $\quad C_2 = 600\ \mu\mu f$
$L_{s2} = 40\ \mu h$ $\quad C_T = 2{,}000\ \mu\mu f$

$$e_{1g} = \left[1 - 0.68 \cos 2\pi \frac{t}{2.94} - 0.32 \cos 2\pi \frac{t}{0.72}\right] E$$

$$e_{2g} = \left[1 - 1.06 \cos 2\pi \frac{t}{2.94} + 0.06 \cos 2\pi \frac{t}{0.72}\right] E$$

Example 2: $L_{s1} = 60\ \mu h$ $\quad C_2 = 600\ \mu\mu f$
$L_{s2} = 40\ \mu h$ $\quad C_T = 600\ \mu\mu f$

$$e_{1g} = \left[1 - 0.82 \cos 2\pi \frac{t}{1.84} - 0.18 \cos 2\pi \frac{t}{0.63}\right] E$$

$$e_{2g} = \left[1 - 1.13 \cos 2\pi \frac{t}{1.84} + 0.13 \cos 2\pi \frac{t}{0.63}\right] E$$

For the loads considered, which correspond to the range of transformer capacities encountered, the periods of the fundamental and the higher frequency oscillations may be simply expressed with good approximation as:

$$T_1 = 2\pi\sqrt{(L_{s1} + L_{s2})\,C_T}$$

and

$$T_2 = 2\pi\sqrt{\frac{L_{s1}L_{s2}}{L_{s1} + L_{s2}}\,C_2}$$

The oscillation at the load is largely of fundamental period, whereas both the fundamental and the higher frequency oscillations appear in comparable proportion at the generator end.

A proper damping resistance in the order of

$$2\sqrt{\frac{L_{s1} + L_{s2}}{C_T}}$$

inserted in series with the inductance $L_s = (L_{s1} + L_{s2})$ practically eliminates the fundamental oscillation; this damping resistance may be distributed along the generator condenser bank. Inasmuch as the higher-frequency oscillation is largely confined between the connecting lead and the generator stray capacity, a proper resistance approximately in the order of

$$2\sqrt{\frac{L_{s2}}{C_2}}$$

inserted in the lead dampens this oscillation. From the viewpoint of the surge at the transformer load, inasmuch as the higher-frequency oscillation is confined between the connecting lead and the generator stray capacity, this oscillation is of practically no importance.

With a proper damping resistance in the generator condenser bank and a plain lead, voltage measurements at the generator show the higher-frequency oscillation

superimposed along the rise of the front. Generally this oscillation disappears before the crest of the wave is reached. It should be noted that even with all superimposed oscillations eliminated, there always will be a difference in the voltage measured at the generator as compared to the voltage at the load; in case of short leads there can be only a theoretical difference between e_{1g} and e_{2g}, and this theoretical difference is confined only to the rise in the front of the surge.

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Discussion

C. L. Fortescue: The importance of this paper lies in the fact that Mr. Bellaschi has demonstrated that what may appear as extremely complicated circuits can be represented with a close approximation by simple circuits such as those shown in Figs. 1a, 1b, 2 and 6.

The circuits shown in Fig. 1 are straightforward and can be solved by the ordinary methods of differential equations or of the Heaviside Operational Calculus. The circuits shown in Figs. 2 and 6 look simple but are considerably more complicated than they appear. However Mr. Bellaschi has shown how a good approximation may be obtained by segregating portions of the circuits, analyzing them separately, and combining the results obtained in the proper manner.

In all experimental and testing work it is of great advantage to be able to check up by calculation results that may be expected under test. One is more apt to have confidence in test results which can be predicted with close approximation by calculations. Mr. Bellaschi has shown in detail in Appendixes 1, 2, and 3, the methods of carrying out the calculations which will apply to most practical cases and he has shown by computed curves *A*, *D*, and *K* how close these computed results check the actual cathode ray oscillograms obtained as marked *A*, *D*, and *K*.

When it was first suggested that standardization of wave form of surges for testing be undertaken I demurred, stating my reason that it would be necessary not only to standardize the waves but also to standardize the surge generator itself for the reason that two surge generators giving the same open circuit wave would not necessarily give the same wave under test conditions. This is no longer to be feared now that Mr. Bellaschi has shown how easy it is to predict the actual wave under test conditions and therefore we may go ahead with specifications for surge testing of apparatus without fear provided that measurements of the surge to which the apparatus is subjected are properly carried out and calculations are made beforehand to insure that the apparatus is receiving the proper test.

F. J. Vogel: There is a particular timeliness to the paper by Mr. Bellaschi. Surge testing of transformers to prove their surge strength is now a common procedure, and the Transformer Subcommittee of the Institute is even now engaged in the formulation of a code for such testing.

There has heretofore been no general understanding of the limitations of the means of testing. Probably most engineers have thought that the characteristics of surges could be easily altered by changing various constants in the generator. For example, data have been published using waves of various fronts and tails. Mr. Bellaschi has shown that specified characteristics can be obtained only within certain limits or with generators of given design. Two of these limitations are very important, particularly for use in the present work of the Transformer Subcommittee, and for the designers of such testing installations.

One limitation is in the steepness of the front of the wave. This is determined by the series resistance, the internal inductance of the generator and the capacity of the transformer. Of these constants, only the series resistance is subject to alteration, as the inductance is inherent in the generator, and the capacity of the transformer is of course fixed. The adjustment of the resistance is determined by the desirability of testing with a wave free from oscillation at the transformer. That this is desirable can be seen from the following facts:

1. The waves generally described in the past in surge testing have given the front and the length of the tail, which are perfectly definite things. If oscillations were permitted, the waves could not be so defined. The frequency and amplitude of the oscillations would vary, and require limitation. Therefore in the interests of simplicity and clearness, the elimination of oscillations is desirable.

2. The elimination of the oscillations will avoid variations in the reported performance of gaps, bushing and insulation. In the earlier surge investigations, the surges obtained for test were often calculated considering only the generator condenser capacity and the load resistance. Oscillations due to inductance and stray capacity were not taken into consideration, and when the voltage was measured by the sphere gap not only were fictitiously high results obtained, but agreement could not be obtained between different observers with different test apparatus due to the difference in oscillations obtained. Similarly if these oscillations are not damped out, the tests by different manufacturers will not be comparative, and they will furnish fictitious values for the tests made.

3. Oscillations will result in surge characteristics not easily predetermined for comparison with the oscillograms obtained by test.

Mr. Bellaschi has shown that oscillations may be eliminated by proper adjustment of the series resistance and that this limits the steepness of the wave fronts which may be obtained. It is further to be noted that this limitation is unavoidable, since there is a limit to which the inductance inherent in any generator can be reduced. However with the series resistance adjusted to damp oscillations at the transformer, wave fronts of from ½ to 2½ μsec can be obtained. These should be satisfactory for transformer testing.

Due to the fact that with certain combinations the crest of the wave is very flat, it is very difficult to make a definite statement as to the length of the entire front of the wave. A similar trouble often exists at the very beginning of the wave. Since these difficulties are often present, it is better to adopt some conventional method of defining the front which will lead to greater uniformity. One method which has been suggested has been to use the time from the beginning of the wave up to 90 per cent of its crest value. This time is in turn multiplied by the factor ten-ninths to obtain the entire front of the wave. Another method which has been suggested is based on the time elapsed between values of 10 per cent and 90 per cent of the crest value of the wave. This time would be multiplied by ten-eighths to obtain the full value of the front of the wave. Either of these two methods appears to be a great advantage in the standardization of wave fronts for transformer testing.

The other limitation is in the maximum length of the surge which can be obtained. In testing insulator strings or gaps the length of the tail of the surge is controlled by the adjustment of the discharge resistance of the surge generator. When testing transformers however, particularly large ones, the inductance of the transformer is so low compared to the discharge resistance that it becomes the controlling factor. The maximum length of the tail that can be obtained therefore depends on the internal capacity of the surge generator and the inductance of the transformer. It has been agreed that a 40 μsec. tail should be suitable for surge testing and the capacity of the Sharon generator was made large enough to secure this length even with the largest transformer.

C. Francis Harding: The profession is greatly indebted to the author of this paper for his detailed analysis of the characteristics of the discharge circuit of the surge generator, particularly with the surge-proof transformer used as a testing load. Obviously, the basic and unchangeable constants of such loads subjected to surge tests greatly affect the characteristics of the impressed wave. Hence the necessity of having cathode ray oscillograms of the exact wave impressed upon the test equipment accompanied by sufficient circuit data or check calculations to convince the purchaser that the oscillogram actually represents the surge potential to which the test specimen has been exposed.

In this connection it is well to point out to the prospective purchaser of surge tested equipment that the inductance of his equipment to be tested is not that which might be measured at 60 cycles nor necessarily that which might have been calculated from the Bureau of Standards formula based upon the geometry of the coils, but rather an equivalent inductance modified, as the result of the high frequency of discharge, by the distributed capacitance of the winding to be tested. Such an equivalent inductance, which the author considers correctly but which is frequently either neglected or incorrectly determined in such tests, may be determined either experimentally or by calculation if the proper rate of change of current is considered. Experimentally, it may be determined by measuring the potential and the discharge current by means of sphere gaps connected in parallel with the test load and a known series resistance respectively. Several such measurements at varying potentials, checked by means of a high frequency timing wave upon the oscillogram, permit the determination of the maximum discharge current and the time in microseconds at which the maximum current of the surge exists. These empirical values, when substituted into the fundamental discharge equations of the surge generator, will provide an approximate value of the equivalent inductance in the discharge circuit. Secondly, the equivalent inductance may be calculated from an oscillogram taken with a minimum of resistance in the discharge circuit. The resultant oscillatory frequency taken from the cathode ray oscillogram may then be used to determine the relation between the known induced potential across the inductive portion of the circuit and the inductance itself (expressed for the frequency of the actual surge discharge). A very close approximation has been secured at Purdue University with the use of these two methods in testing so-called surge-proof distribution transformers and other high-voltage equipment.

C. M. Foust: This paper on impulse testing of transformers is timely and valuable. The application of rigid mathematical analysis to discharge circuit conditions is to be commended. Added significance is obtained for sphere gap and cathode ray oscillograph measurements when they are interpreted in terms of capacitance, inductance and resistance constants of the impulse generator and connected circuits.

Several points in this paper invite questions but the interest of those engaged in impulse testing work is attracted particularly to the electrical mechanism of the discharge circuit and the circuit constants.

Referring to Table II and the oscillograms of the paper capacitance C_2 is the ground capacitance of the condenser bank structure, capacitance of the sphere gap and leads and is taken as approximately 600 $\mu\mu$f. I assume that this value was chosen in accordance with the frequency and amplitude of the superimposed oscillations on the oscillograms. To me this 600 $\mu\mu$f. is considerably more than expected. A 150-cm. diameter sphere gap capacitance would not be in excess of 100 $\mu\mu$f. and a 100 ft. lead not in excess of 50 $\mu\mu$f. by calculation. This would leave 450 $\mu\mu$f. for the grand capacitance of the condenser bank structure. It is somewhat difficult to accept so high a figure in view of general experience with such circuit constants. On the basis of an 0.008 μf. capacitance for the impulse generator to ground this stray capacitance of approximately 450 $\mu\mu$f. is about 6 per cent of main capacitor C_s.

Some data and oscillograms taken in Schenectady are of interest on this point. Circuit constants of the impulse generator were arranged for a (1/2-5) wave. The capacitance C_s was 0.0083 μf., the inductance L_s 80 microhenrys and the load resistance 650 ohms. No added series resistance R_s was inserted. Oscillograms of wave shapes were taken as follows:

1. With the discharge circuit alone.
2. Discharge circuit with 8-unit string connected.
3. Discharge circuit with a 50-cm. diameter sphere gap connected.
4. Discharge circuit with the insulator string and sphere gap both connected.

The wave shapes are shown in Fig. 1. The oscillations are very evident on the crests of the waves. That they are less pronounced than several of those shown by Mr. Bellaschi is, of course, partly due to the use of a low load resistance R_L. Analysis of these oscillograms gave the following results:

	Capacitance C_L from oscillograms $\mu\mu$f.
1. Circuit alone	65
2. Insulators	95
3. Sphere gap	90
4. Insulators and sphere gap	125

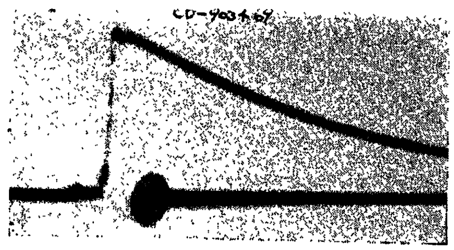
A more thorough presentation of these data is given in the *General Electric Review* for July, 1932.

These data give a value of 30 $\mu\mu$f. for the insulator string, 25 $\mu\mu$f. for the 50-cm. diameter sphere gap and 60 $\mu\mu$f. for the two in parallel. Such values appear very reasonable when compared with calculated values. The 65 μf. stray capacitance to ground of the impulse generator is less than 0.8 of 1 per cent of the main capacitor C_s. In view of such experience it becomes difficult to accept the 600 $\mu\mu$f. value for C_L given by the author. This point appears to deserve further attention and any comments Mr. Bellaschi wishes to make will be appreciated.

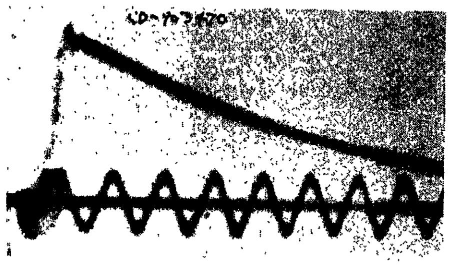
W. L. Lloyd, Jr.: Mr. Bellaschi's paper is timely, well written and interesting but the subject is not particularly new to our laboratory staff. Since Mr. Peek's first lightning generator of 1913, the impulse voltages delivered by such a circuit have been subject to calculations. On page 1916 of the A.I.E.E. TRANSACTIONS for 1915 can be found a discussion by Mr. Peek of the effect of load capacitance upon the impulse generator test voltage. This effect and other variables were considered by Mr. Peek in 1915 when he first described his impulse generator at the San Francisco Convention.

The calculations were first carried on by the laborious solutions of conventional mathematics and subsequently by the shorter methods of Heaviside's Operational Calculus. From the beginning these calculations could be, and were, checked by the sphere-gap. After 1925 the cathode ray oscillograph was used to check the calculations. When the cathode ray oscillograph was developed it was gratifying to see how closely it checked the previous calculations and test results. Of course, it *had* to check

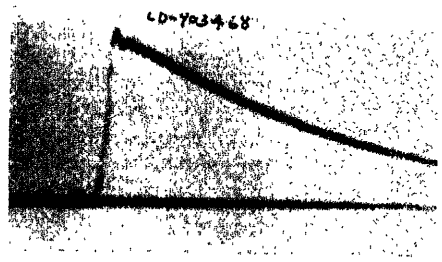
for the sphere gap had furnished a check on the calculated voltage. If the calculated voltage was correct then the calculated wave shape had to be correct also. But the independent check by the oscillograph was quite convincing and also accelerated the laboratory work. Oscillograms were often quicker to obtain than calculated results even by Heaviside's Operational Calculus. The electrons decide what they are supposed to do and do it in a few microseconds, whereas man's brain sometimes takes a few hours to predict their operation. The oscillograph, therefore, became a valuable laboratory tool and with the sphere gap has



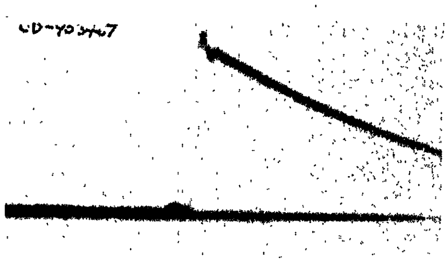
Discharge circuit only



Discharge circuit with insulator string load



Discharge circuit with sphere gap load



Discharge circuit with sphere gap and insulator string load

FIG. 1

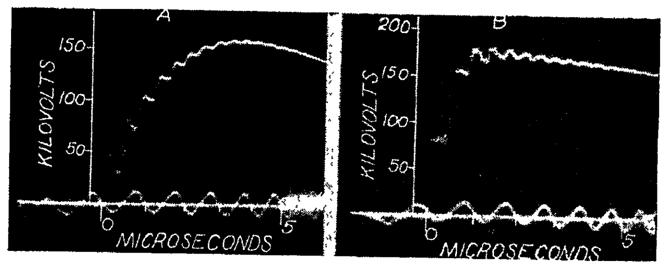
furnished important checks on the mathematical work upon the impulse generator circuit.

These calculations have, however, been going on continuously since 1913 and much of the material which Mr. Bellaschi has given is fundamental and now pretty generally known. At least, in the laboratory, every-day use is made of the conclusions which he reaches in his paper. It is because of knowledge of these fundamental facts, that we have made so much progress on lightning research in the last ten years.

In our work we have found it necessary to go much more completely into the subject than Mr. Bellaschi has, particularly upon the effects of changes in the various circuit constants and different load conditions. This is especially necessary when impulse tests are made on large power transformers fully excited. A more thorough study on this subject has recently been made and the results are embodied in a paper entitled "The Production of Artificial Lightning in the Laboratory," by W. L. Lloyd, Jr. and J. C. Dowell which it is hoped will be published at an early date.

C. S. Roys: The ability to arrange a surge generator circuit in a manner such as to produce a wave of known form is becoming increasingly important in the testing of various electrical devices. Up to the present time it has been customary to consider a simple series circuit as the equivalent network of a surge generator and its test circuit under discharge conditions, determining the constants by methods that do not include the effect of capacity to ground, etc. Such a procedure does not give results that conform with observed ones, and this is especially true along a wave front, the most important portion of the wave in the majority of the tests.

By assuming an equivalent network in which consideration is given to the capacity to ground, although certain effects have been neglected, it is felt that the author has made a notable advance toward the complete understanding of the situation. So far as the tails of the waves are concerned, the validity of the assumptions is well established by the close agreement between the calculated waves and the ones determined by means of the cathode ray oscillograph. Unfortunately, however, the actual wave fronts are hardly discernible on the oscillograms and no close check can be made on the steepness of the wave fronts.



OSCILLOGRAMS A AND B

Also, the nature of the high frequency oscillations and reflections is not apparent, these latter having been found to be of considerable importance in many instances.

In conclusion I wish to express the hope that the author will continue this line of investigation, being particularly careful to obtain clear records of the wave fronts. Only then will it be possible to say as to whether or not one can neglect the effect of reflections and high frequency oscillations under a similar set of conditions, and in consequence, assume the simple equivalent network of lumped constants.

C. S. Sprague: The author presents an excellent analysis, based upon lumped constants, of surge generator characteristics when the generator is connected to a capacity load, and shows that by the insertion of the proper value of series resistance, the oscillations due to the total load capacity and the inherent inductance of the generator circuit may be effectively damped. The actual oscillograms check well on the tail of the wave with the calculated curves from equations derived on the basis of lumped constants.

For surge testing of insulators, bushings and lightning arresters, the front of the wave is of prime importance, and the writer believes that equations derived on the assumption of lumped constants do not hold on the rising front of the wave. Oscillograms have shown that the finite length of the connections of the generator circuit gives rise to reflections across the load resistance, which reflections are not usually negligible when a smooth front is desired. In other words, during the first few

instants following breakdown of the main generator gap, the circuit acts in a manner analogous to a transmission line, grounded through an impedance at one end. Reflections take place in the same manner except that due to the much shorter length of circuit involved, the frequency of reflection is much higher.

Oscillograms A and B illustrate these reflections, in this case the reflections being negative on both oscillograms. The following circuit, Fig. 2, illustrates the conditions under which these oscillograms were taken. The surge generator was not loaded, except for the capacity of the potentiometer and measuring sphere gap.

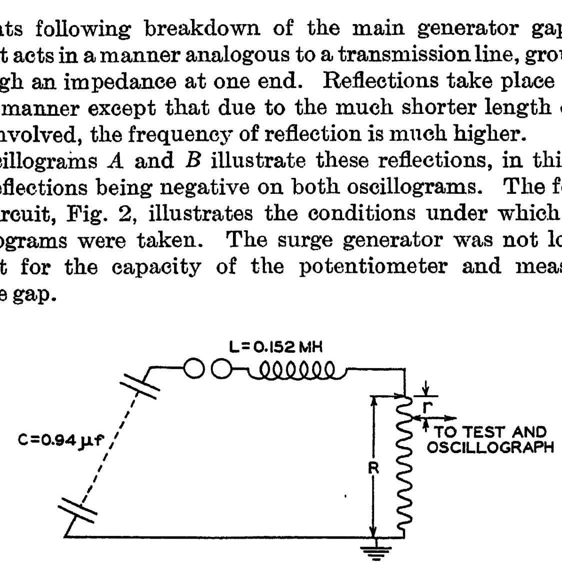


FIG. 2

Length of wire between generator and resistance = 171 ft.
For oscillogram A, R = 175 r = 19
For oscillogram B, R = 825 r = 69
Inductance L composed of 5 turns No. 22 wire, spaced 2 in., wound on an octagonal form, 10 ft. across corners. The value given above was calculated from Nagoska's formula assuming a circle of equivalent area

Each oscillogram shows a frequency of reflections of 2.5 megacycles. On the basis of the speed of propagation being 1,000 ft. per microsecond, these reflections would take place on a line 200 ft. long, whereas the measured length was 171 ft. between the generator and the resistance.

Oscillogram A shows that with 175 ohms series resistance, the wave requires about 10 reflections to reach a peak in approximately 3½ microseconds, while with 625 ohms, oscillogram B indicates that the peak is reached in three reflections in about 1 microsecond. Very obviously neither of these waves would be satisfactory test waves where a reasonably smooth front is desired. On the other hand sufficient capacity in the load would help to smooth out the ripples, but such loads as arresters, insulators or bushings would affect these waves very slightly.

In view of the above reasoning there seem to be two methods by which one may obtain a wave relatively free from oscillations on the front.

The first is analogous to grounding the end of a transmission line through a resistance equal to its surge impedance; in other words, so to adjust the total resistance in the circuit that reflections do not occur at the junction of the inductance and resistance. It is obvious that once this condition is obtained, only loads of low capacity and with short leads can be connected without changing the wave front. This method can be used only for the steepest waves and then the range of steepness may be quite limited for the usual possible variations in resistance.

The second method is to use a resistance low enough to make the individual reflections quite small compared with the main wave. This method is applicable to the slower waves. Oscillogram C illustrates a wave of 50 kv./μ sec front, obtained using this method.

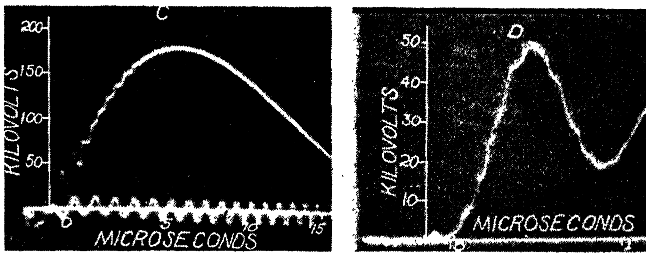
Using this latter method usually requires that additional series inductance be inserted in the discharge circuit. It has been the practise to construct such an inductance on a long, small diameter form, the purpose being to keep the volts per turn down to a small value. An inductance of this type is inefficient as regards the length of wire necessary to secure a given value of inductance. It has been determined experimentally and is in accord theoretically that to keep the reflections across the added series inductance of small magnitude, the inductance value should be obtained with a minimum length of wire. This means a large diameter, short length inductance with turn spacing as small as possible without flashover occurring between turns. This latter type gives a larger number of small reflections as compared with the long narrow inductance which gives a smaller number of large reflections.

It is unfortunate that so many of the cathode ray oscillograms appearing in this and other articles, lack detail on the front, and even if the front were visible the sweep is usually so slow that no accurate determination of the oscillations on the front of the wave is possible. The writer is fully aware that due to the high speed of beam travel across the film, this is the most difficult part of the wave to record, but believes that the advantage of recording the front of the wave is well worth the extra care and trouble required. Oscillogram D illustrates this point by showing a wave reaching a peak in about ½ microsecond, with a sweeping speed such that one microsecond occupies about 2 inches of the time axis. With an amplitude of approximately 3 inches, this spreads out the wave front so that oscillations may be accurately determined.

P. L. Bellaschi: The primary purpose of the paper was to analyze the fundamental factors that must be considered in any attempt to formulate a code for the surge testing of electrical apparatus, such as transformers. It was also the object of the paper to stimulate thought and criticism on the subject. The foregoing discussions are in themselves testimony that the results accomplished have well compensated our labors.

We cannot overemphasize the advantages of simple, but, none-the-less rigorous methods of analysis, particularly when dealing with engineering problems. Dr. C. L. Fortescue's advice and comments on this subject fully deserve our attention.

The questions on wave form discussed by Mr. Vogel are of vital importance. Results obtained by different investigators cannot be compared with the expectation of agreement, unless the same "yardsticks" are established and used by all.[1] The first yardstick in surge testing that requires establishing is the wave form of the surge voltage applied to the apparatus tested. The second yardstick is the method of measurement of the surge voltage. The correct control of the surge generated, supplemented with analysis of the test circuit, and combined with the proper method and technique of surge voltage measurement should facilitate general agreement of results between different investigators. Regardless of Mr. Lloyd's claims in his discussion, the experimental work on surge voltages done previous to the advent of the cathode ray oscillograph and previous to the extensive investigations of the past four or five years will remain, to be sure, of historical interest, but hardly to be used with full confidence at the present. We do not subscribe to Mr. Lloyd's forced reasoning, on the question of his calculations and measurements, that this and that *had* to check. Further discussion on the measurement of surge voltages will be duly con-



OSCILLOGRAMS C AND D

1. See, for example, *SEV Bulletin*, September 16, 1931, bottom of p. 473, second column, for disagreement in results between two different investigators, one using a smooth wave and the other unknowingly using a wave with superimposed oscillations.

sidered at the A.I.E.E. Winter Convention (1933) where the writer and others are presenting papers on the subject.

Professor C. F. Harding raises a pertinent question: the determination of the equivalent surge constants of the apparatus tested. These constants may be determined either experimentally by the proper methods, which he describes, or by calculation when the circuit constants under surge conditions of the transformer windings and also of the apparatus connected to the windings are taken into account and replaced by an equivalent simple circuit, when possible, as shown in the paper. The surge characteristics of transformer windings comprise a subject in itself of great importance.[2]

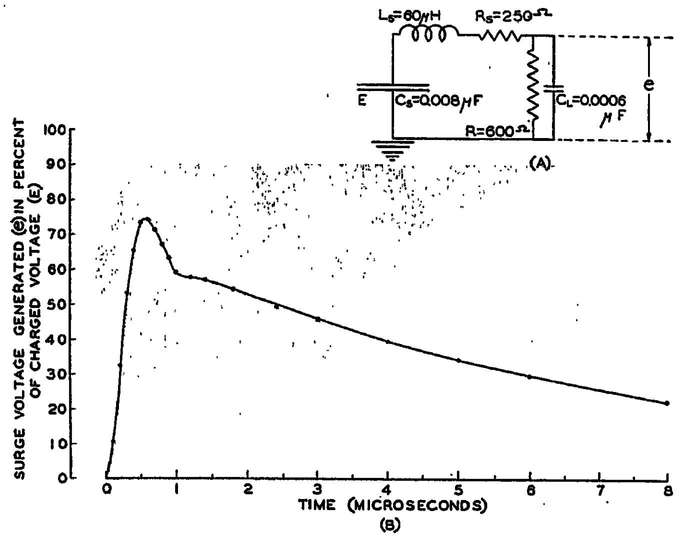


FIG. 3

The question raised by Mr. C. M. Foust on the circuit constants of the generator, particularly the point in regard to the stray capacity of generators is answered in full details in the following:

The surge generator capacity C_s, the load resistance R and the inserted resistance are determined by measurement on the individual elements. The effective stray capacity C_2 of the generator can be determined in a number of ways. Our estimated value of this capacity from the physical dimensions of the generator, taking into account the capacity of the auxiliary equipment connected to the generator and the capacity of the generator structure to ground, gives us a figure close to the value given in Table II of the paper. Experimentally, the capacity C_2 and inductance L_s may be determined closely from the relations

$$\frac{T_1}{T_2} = \sqrt{\frac{C_2}{C_2 + C_A}} \text{ and } T_1 = 2\pi\sqrt{L_s C_2}$$

where T_1 and T_2 are the fundamental periods of the superimposed oscillation on the wave without and with a known capacity load C_A. In such measurement all inserted resistance in the generator is removed and the load resistance is adjusted to a large value. The values of C_2 and L_s may also be determined from the fundamental period

$$T_1 = 2\pi\sqrt{L_s C_2}$$

in conjunction with the critical damping resistance

$$R_s = 2\sqrt{\frac{L_s}{C_2}}$$

The inherent resistance of the generator may then be estimated from the damping factor of the superimposed oscillation (the damping factor of a C-L-R series circuit is given by $\epsilon^{-\frac{R}{2L}t}$), provided all inserted resistance is removed and the load resistance is made sufficiently large relative to its critical damping value: $\frac{1}{2}\sqrt{\frac{L_s}{C_2}}$. A further check of L_s and of the inherent resistance may be had by short-circuiting the load resistance and removing all internal resistance. From the oscillogram thus obtained—*i. e.*, from the period and damping of the oscillation on the film, in conjunction with the known capacity C_s, the equivalent constants L_s and R_s (inherent) may be estimated. These are simple and practical methods based on lumped circuit constants which have proved adequate for engineering purposes; though, strictly speaking, in considering the general subject rigorously from a scientific viewpoint, under certain conditions and for certain cases discussed further on, consideration need be given to the distributed circuit constants of the condenser bank of the generator. In accordance with the engineering methods described above, the values of the circuit constants reported in the paper have been found. The close agreement between calculated surge voltages and the oscillograms justify the above methods for engineering purposes and for surge generators such as used for the purpose described.

We cannot compare surge generators unless they are on a par generally. The 3,000-kv. surge generator at Sharon is of liberal design. Accordingly the stray capacity of the generator alone is large. The value of C_2 is not only that of the generator alone, but includes the capacity of parts permanently connected to it, such as the 200-cm. sphere gap, insulators, lead, etc. The value of $C_2 = 600\ \mu\mu$f. is the correct one to use for this generator. Inasmuch as loads tested may assume values

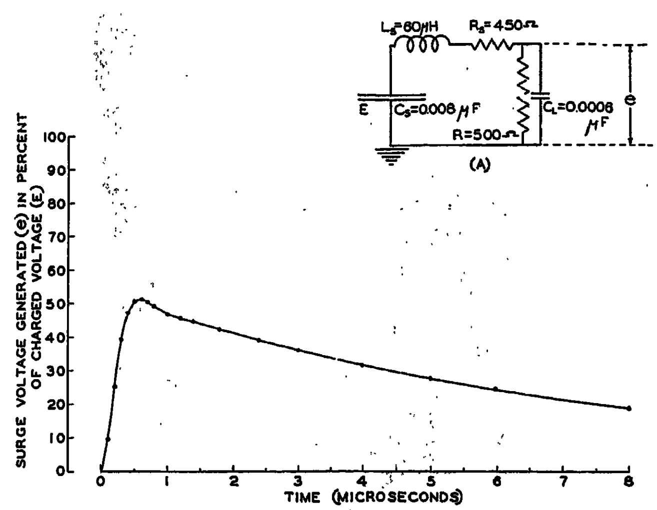


FIG. 4

for the load capacity C_T as large as five times the stray capacity of the generator, it would be immaterial on this score whether C_2 were greater or less than what it is. One of our smaller surge generators, which for comparison purposes falls within the classification of the one Mr. Foust describes, has a stray capacity $C_2 = 125\ \mu\mu$f., including in this the structure of the generator, a 25-cm. sphere gap, an insulator string, a capacity potentiometer and a resistance potentiometer. Our figure for our small generator is identical to that given by Mr. Foust for his generator.

Mr. Foust's oscillograms have not been reviewed by the writer, but very likely these are identical to those in Fig. 15 of

2. See, for example, Appendix to P. L. Bellaschi's: "Transformatori a mantello antirisonanti" *L'Energia Elettrica*, April 1932-X.

his well-written article in the *General Electric Review* for July 1932. Mr. Foust states in his discussion that no added series resistance R_s was inserted. These oscillograms have an appreciable oscillation superimposed on the crest of the wave, particularly when an insulator string and a 50-cm. sphere gap are connected to the generator—which is the circuit condition that is of practical interest. We appreciate that the primary purpose of these oscillograms was to estimate or determine the

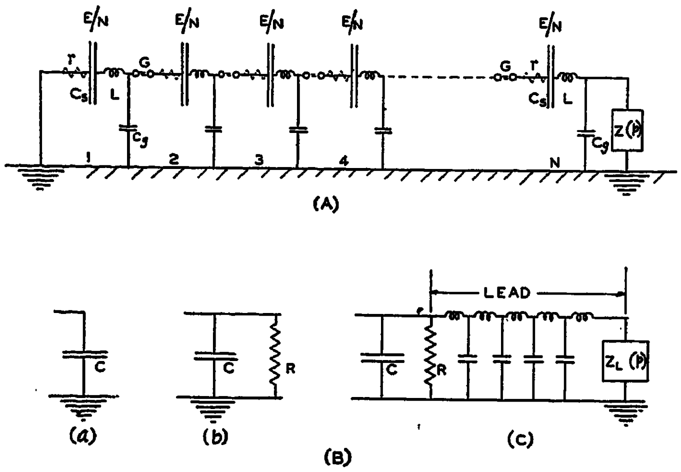
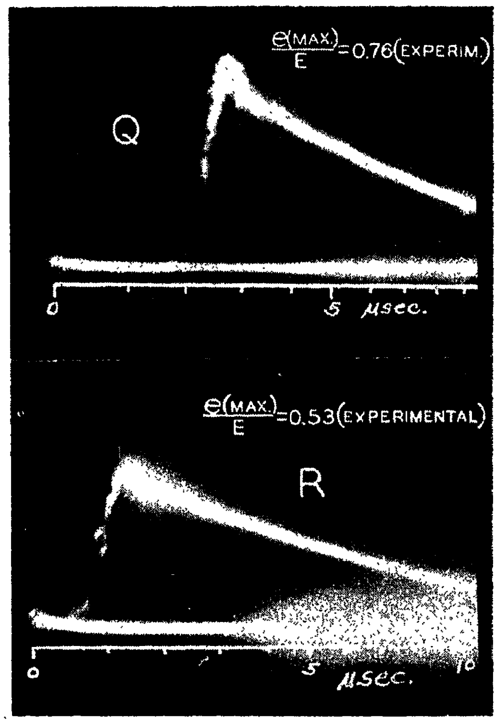


Fig. 5

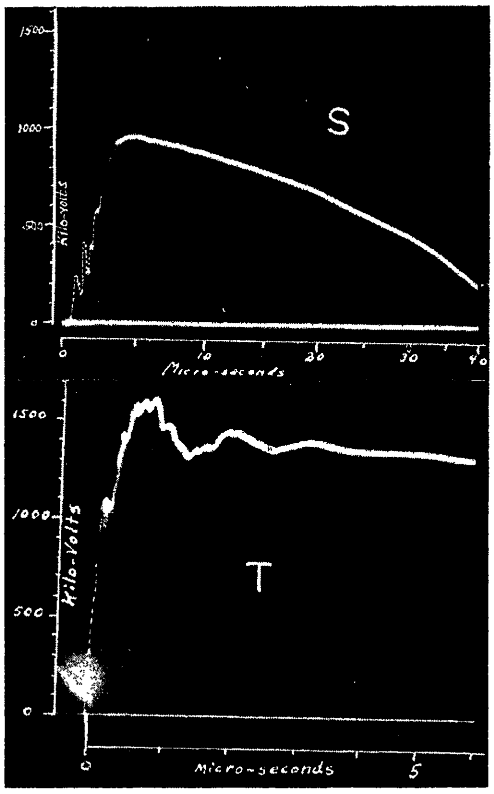


Oscillograms Q and R

effective capacity of the various insulation structure loads; such is our interpretation. We hope, however, that the wave with the marked superimposed oscillation is not being used as a standard wave. A similar example to that of Mr. Foust's is shown in oscillogram *Q*. The constants of the generator circuit for this oscillogram are given in Fig. 3A. Substitution of these circuit constant values in the fundamental equations in Appendix I of the paper, gives the following equation for the voltage generated:

$$e = \left[\epsilon^{-0.143t} - \epsilon^{-3.40t} \left\{ 0.606 \sin \frac{2\pi}{1.17} t + \cos \frac{2\pi}{1.17} t \right\} \right] 0.704\, E$$

where t is in microseconds. This equation is plotted in the curve of Fig. 3B. This wave as well as the one of Mr. Foust, we have referred to, are unsuitable as a standard for surge testing of gaps, insulators and similar insulation structures for which the short wave would be used in addition to the (1½-40) wave. This type of wave may have been, and very likely it was, used in the *pre-cathode ray oscillograph epoch* to which Mr. Lloyd refers to and before the thorough analyses of the problem which have been made lately, but such a wave form is unsatisfactory at



Oscillograms S and T

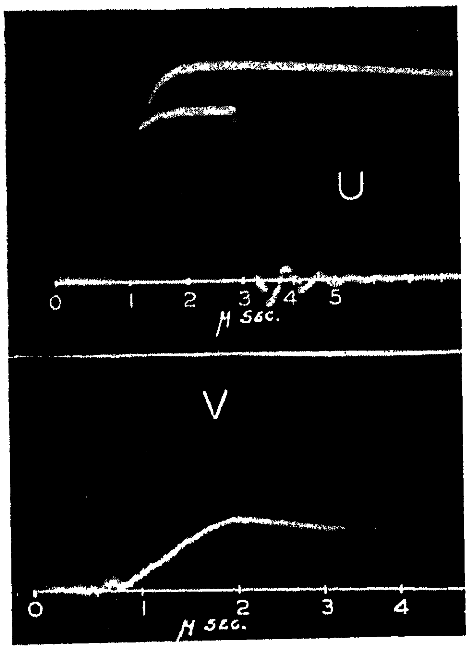
the present time. To give this wave a closer semblance to what the standard (½-5) wave should be, the generator circuit constants are adjusted as shown in Fig. 4A. Again, from the fundamental equations in Appendix I of the paper, the equation of the surge voltage generated for these circuit constants is:

$$e = \left[\epsilon^{-0.130t} - \epsilon^{-5.35t} \left\{ 1.05 \sin \frac{2\pi}{1.26} t + \cos \frac{2\pi}{1.26} t \right\} \right] 0.533\, E$$

where t is in microseconds. This equation plotted gives the curve in Fig. 4B. Oscillogram *R* gives the measured wave form and the regulation. This is a more desirable form of wave to use than any of the previous ones mentioned. The ripples or lead oscillations along the rising part of the front of the surges shown

could be removed if that need be, likewise the regulation could be improved. These oscillograms are shown here for illustration purposes, to make clear our objectives in this question of standard wave form.

We are in sympathy with Messrs. C. S. Roys and C. S. Sprague on the question that published oscillograms do not always show the rising part of the front. The oscillations due to the lead and to the distributed constants of the condenser bank of the generator, mentioned in the paper, are present in our case only on a small part of the front along the rise; but unfortunately due to the relative rate of travel of the cathode beam, when the whole wave is recorded, the part on the front, as compared to that on the tail, is relatively faint on the original oscillograms so that in the course of reproduction and printing of the oscillograms the



OSCILLOGRAMS U AND V

rapid oscillations in question are completely lost. Oscillograms S and T, here shown, are practically prototypes respectively of K and B in the paper, except that in S and T the time sweep is faster. Oscillogram S is of practical interest. It shows that the rapid oscillations disappear along the rising part of the front. In our case, these rapid oscillations are largely due to the lead mentioned in the paper and can be calculated, if need be, as shown in Appendix III.

We agree with Messrs. C. S. Roys and C. S. Sprague that the theoretical circuit of the condenser bank of the surge generator is a distributed circuit, as shown in Fig. 5A. We have always appreciated this fact and also the considerations connected therewith. We shall point out briefly that under certain conditions the condenser bank of a surge generator corresponds closely to a very short transmission line. In the case of a condenser bank disposed with respect to ground such that all condensers are equally spaced from ground, the circuit constants approach the uniformly distributed arrangement of the circuit in Fig. 5A, and provided there is no appreciable load effect due to $Z(p)$, this circuit would act closely to a line, more so if C_s is very large compared to C_g. In such a case, as stated correctly by Mr. Sprague, a terminal resistance equal to the impedance of the line would prevent reflections at the terminal end.[3] The natural oscillations of circuit Fig. 5A with load $Z(p)$ removed are determined from[4]

$$\cosh \sqrt{LC_g w^2 + \frac{C_g}{C_s}}\, N = \cos j \sqrt{LC_g w^2 + \frac{C_g}{C_s}}\, N = 0$$

where

$$j \sqrt{LC_g w^2 + \frac{C_g}{C_s}}\, N = K \frac{\pi}{2} \text{ and } K = 1, 3, 5, \text{etc.}$$

The solution of the voltages in such a circuit is arrived at in much the same way as the solution for finite segments of a line, introducing boundary conditions as indicated from Fig. 5A. A detail analysis of this subject is beyond the scope of this discussion. The method of analysis is as outlined above.

The type of surge generator used is built vertically, comprising of three stairs arranged in zig-zag fashion.[5] In such a case the stray capacity of the generator alone, from the terminal end to ground, acts in effect largely as a lumped capacity in parallel with the generator. In addition, the stray capacity of parts permanently connected to the generator at the terminal end is appreciable, and this, too, acts as a lumped capacity. Any effect due to distributed capacity, which theoretically is always present, becomes in this case, practically speaking, of secondary importance in so far as the voltage at the terminal end is affected. The effect due to any distributed capacity present would appear as oscillations of higher frequencies compared to the natural fundamental oscillation superimposed on the wave, these being largely confined at the rising part of the front and reduced in magnitude at the terminal end due to the large effective terminal capacity. The distributed series resistance inserted in the generator would also tend to reduce the effect of these higher frequency oscillations by damping them. Furthermore in practise loads such as (a), (b), (c), indicated in Fig. 5B, modify considerably the effect at the terminal end due to any distributed capacity present. Fundamental considerations and experimental results thus show that for the type of surge generator and for the conditions of test discussed in the paper lumping the circuit constants of the generator is justified.

Using the ground end stair of our 3,000-kv. generator (equivalent to 1,000-kv.), with the large stray capacity C_2 at the terminal end of the circuit and with the proper series resistance R_s, we obtain oscillograms as shown in U. The fronts here rise smoothly and are of the satisfactory type, as Messrs. Roys and Sprague mention, to test gaps and similar apparatus along the rise of the front. Oscillogram V was taken with a smaller generator, using a series inductance and a series resistance, in conjunction with the load capacity available, to secure a smooth front. The wave rises almost at a constant rate from zero to crest voltage. Increasing the crest voltage of this oscillogram automatically increases the rate of rise of the front. A more rapid sweep of the cathode beam along the time axis could have been used or a greater sensitivity of the voltage divider and cathode ray oscillograph could have been employed, if it were necessary.

3. See also, for example, article by J. Kopeliovitch on impulse testing of insulators, *SEV Bulletin*, Sept. 16, 1931, bibliographical reference (33), for investigation with cathode ray oscillograph on damping of 20 meter line.

4. O. Heaviside, "Electromagnetic Theory," Vol. 2, p. 127, and sequel.

5. O. Ackerman, "New Surge Generator for Testing Transformers," *Electric Journal*, February 1932, p. 61.

Characteristics of Load Ratio Control Circuits

For Changing Transformer Ratio Under Load

BY L. F. BLUME*

Associate, A.I.E.E.

Synopsis.—*The influence of saturation phenomena in series reactors on the circuit performance of load ratio control equipment is discussed. It is shown that unless care is exercised in the design of these reactors, gross distortion may be introduced into the circuit, resulting in obtaining across the reactor voltage peaks which on the one hand may endanger the insulation, and on the other hand greatly increase the rupturing duty on the circuit breaking devices. Formulas are developed which show what proportion of line voltage is absorbed by a series reactor subject to magnetic saturation. It is shown that this voltage can be expressed in terms of the reactive constants of which the circuit is composed, and that it is independent of the current or voltage wave form. Numerical solutions are given in the shape of curves, assuming that the magnetic circuit of the reactor is made up of typical transformer steel. The great influence of a small air gap in the magnetic circuit in reducing these voltages is shown.*

* * * * *

In previous articles† the circuit characteristics of typical transformer connections used for changing transformer ratio under load have been discussed. It was shown that the performance of the equipment is dependent upon the design characteristics of the reactor employed, and also upon which positions are selected by the transformer designer, from the three possible, for the permanent operating position. It was shown that in the design of the reactor used, two conflicting considerations must be kept in mind, namely, that in the position where the reactor is connected across adjacent taps (bridging position) the resultant magnetizing current in the reactor should not be excessive, and on the other hand in the position where the reactor is in series with the load, (unsymmetrical or series position), the reactance introduced into the circuit should be maintained low. The reactor design is a compromise between these considerations. In other words, in order to avoid excessive series reactance being introduced into the series positions, it is necessary to design the reactor so that when connected across adjacent taps a comparatively large circulating current flows.

It was also shown that the best circuit performance is obtained when in the operating position the connection is made on one tap only, and with the reactor short-circuited. With permanent operation only on this connection, the voltage steps obtainable become uniform, and the minimum impedance is introduced into the circuit. This entails the provision in the transformer design of a transformer tap for every operating position. It also has the advantage that in the process of switching from one transformer tap to the next, the operation consists in the quick succession of a number of relatively small steps, which means that a smoother transition takes place during switching.

In the previous articles it was assumed that the reactor used possessed linear characteristics. The purpose of the present paper is to discuss the influence of magnetic saturation of the reactors on performance and to indicate the important part which a relatively small air gap provided in the reactor plays in preventing abnormal and dangerous voltage distortions.

Series Reactor Designed with a Closed Magnetic Circuit‡

The importance of designing a reactor with a large magnetizing current—and with an air gap, so as to obtain essentially uniform inductance for all values of current—can best be appreciated by discussing the characteristics of a reactor having a closed magnetic circuit.

A reactor with a closed magnetic circuit can be readily designed so that the magnetizing current on the bridging position is kept small, say less than 10 per cent, and at the same time excessive reactance drop in the unsymmetrical or series position may be avoided by designing with high magnetic densities so that the load current will saturate the iron. Thereby the reactor becomes appreciably smaller and inherently less expensive.

By this means the effective value of the reactance drop can be maintained low, even with a load current equal to as much as ten times normal magnetizing current. However, when this is done excessive voltage peaks are introduced into the circuit, due to the distortion effects of magnetic saturation, which may result in dangerously high voltages being induced in the reactor.

This phenomenon is due to the fact that the ohmic value of the inductance of a closed magnetic circuit varies between very wide limits depending upon the instantaneous values of the flux density in the iron. When the current and therefore the flux is passing through zero, the iron is unsaturated and the inductance of the reactor may be several thousand times as much as when the densities approach or exceed 100 kilolines per square inch.

The simplest case to consider is a pure inductive load. In the unsymmetrical position of operation, Fig. 1, the inductance L of the load is in series with the variable inductance of series reactor L^1; and therefore the current being common to both inductances the division of

*General Electric Co., Pittsfield, Mass.

†See items 1 and 4 of bibliography.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

‡For a general description of the effect of saturation on voltage distortion see "Theory and Calculation of Electric Circuits," C. P. Steinmetz, p. 146.

circuit voltage between the reactor and the load at any instant is directly proportional to the ratio of inductances. The voltage drop across the reactor is

$$\frac{e_r}{E} = \frac{L^1}{L + L^1} \quad (1)$$

where

e_r = voltage across one-half of reactor instantaneous value
E = circuit voltage instantaneous value
L = combined inductance of load and transformer
L^1 = inductance of reactor, instantaneous values

The above formula for the instantaneous values of voltage absorbed by the reactor, is applicable to reactors having variable instantaneous value of in-

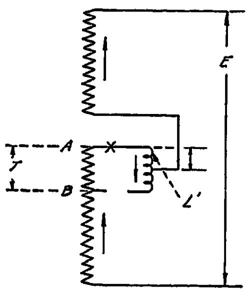


FIG. 1—LOAD RATIO CONTROL CONNECTION SHOWING REACTOR L' CONNECTED IN THE UNSYMMETRICAL OR SERIES POSITION

ductance and also for reactors in which the inductance is constant. In other words the formula applies to both classes of reactors—those in which ample air gaps are provided and also those in which the magnetic circuit is entirely made up of iron. It can therefore be used to compare the two types of reactors from the point of view of the voltage distortion introduced by magnetic saturation of the iron. The formula, however, is strictly limited to pure inductive loads.

From the formula it is evident that the value of peak voltage is independent of the shape of the current wave. Saturation of the reactor iron results in a distortion of the current wave as it approaches and passes through zero, but this distortion has no influence on the magnitude of the voltage peaks. The amount of voltage distortion therefore is entirely determined by the variability in the magnetic circuit, that is, by the magnetization curve of the reactor. Consequently it is very much affected, first, by the value of the maximum flux density within the iron and, second, by the amount of air gap, if any, provided in the reactor.

Voltage distortion curves for various conditions are plotted in Fig. 2. Curves 1, 3 and 5 are for reactors having a closed magnetic circuit, whereas in the case of curves 2 and 4 the reactor is provided with a 1 per cent air gap. The great difference between the values of voltage peaks for reactors with and without a gap is illustrated by these curves. Comparing the three curves corresponding to zero air gap with each other, curve 1 corresponds to a maximum density within the iron of 75 kilolines per square inch, whereas curves 3 and 5 correspond to a maximum density within the iron of 100 kilolines per square inch, showing that increasing the maximum density to saturation values and beyond very greatly increases the voltage peak across the reactor. Curves 3 and 5 are identical except for the fact that the latter corresponds to a load current equal to the normal magnetizing current in the reactor, whereas curve 3 is a condition in which the load current is approximately three times normal magnetizing current.

The numerical values of these voltage peaks for various conditions are given in Table I. These values are arranged to show the influence on peak voltage of:

a. The amount of air gap provided in the reactor.

b. The maximum flux density for which the reactor is designed.

c. The value of normal voltage between adjacent transformer taps.

d. The amount of the zero power factor load, ex-

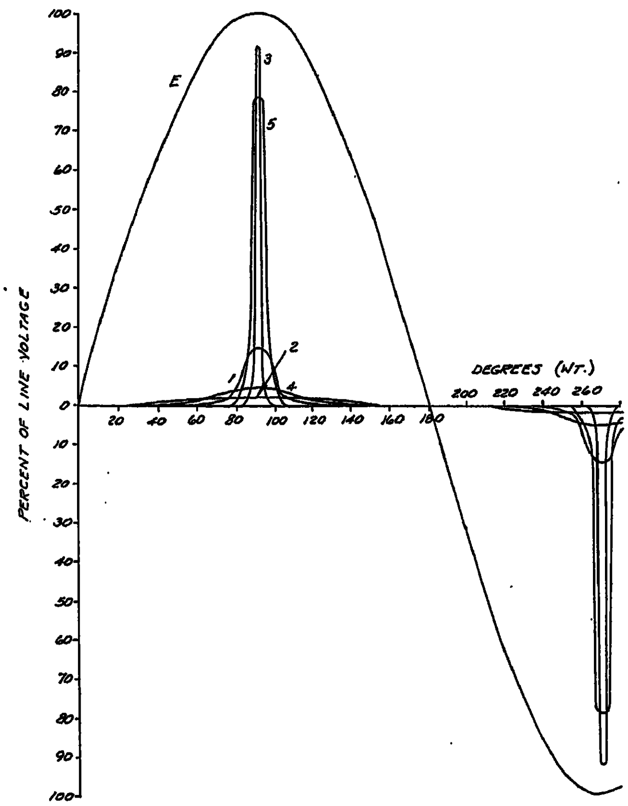


FIG. 2—VALUES OF PEAK VOLTAGES CAUSED BY MAGNETIC SATURATION OF REACTOR

pressed as a function of the normal magnetizing ampere turns of the reactor.

It is important to note that the values of $\frac{e_r}{E}$, given in this table are the voltages appearing across the reactor half, and as this voltage is induced in both halves of the reactor, the total voltage appearing across reactor terminals is twice this value. The table indicates that

in the reactor unprovided with air gaps and designed normally for a voltage of less than 10 per cent of circuit voltage, it is possible to obtain across its terminals peak voltage considerably in excess of circuit voltage. This peak voltage not only is impressed on the internal insulation of the reactor, but also appears across the open contactor. As it appears across the contactor when it is opened during the process of switching, it is evident that the rupturing duty of the contactor is greatly increased.

The quantitative values given in the table have been obtained directly from the formula (4) derived in the appendix. This formula has also been expressed in curve form, Fig. 3 corresponding to a flux density of 100 kilolines per square inch, and Fig. 4 corresponding to a maximum flux density of 75 kilolines per square inch. In both of these curves, solid lines represent a reactor designed for 2½ per cent of the circuit voltage and the dotted lines for 5 per cent of the circuit voltage. Curves are given for zero gap and for 1 per cent, 2 per cent and 100 per cent gaps. These curves are plots of formula (4) derived in the appendix.

TABLE I

Values of $\frac{e_r}{E}$ for $l = 1$

G	$T = 2\frac{1}{2}\%$ 75 kl.	$T = 2\frac{1}{2}\%$ 100 kl.	$T = 5\%$ 75 kl.	$T = 5\%$ 100 kl.
100%	1.26%	1.2%	2.5%	2.4 %
2%	1.26%	1.5%	2.5%	3.08%
1%	1.26%	1.8%	2.5%	3.6 %
0%	15 %	80 %	26 %	89 %

Values of $\frac{e_r}{E}$ for $l = 3$

G	$T = 2\frac{1}{2}\%$ 75 kl.	$T = 2\frac{1}{2}\%$ 100 kl.	$T = 5\%$ 75 kl.	$T = 5\%$ 100 kl.
100%	3.5%	3.5%	7%	7%
2%	3.5%	4.5%	7%	9%
1%	3.5%	5 %	7%	10%
0%	34 %	92.5%	52%	96%

l = load. When $l = 1$, a load current is flowing, which produces in the reactor, when operating in the unsymmetrical position, a magnetizing ampere turns (maximum values) equal to the normal magnetizing ampere turns of the reactor. When $l = 3$ the load current is approximately three times that value.

T = transformer tap in per cent of line voltage.

G = reactor gap in per cent of total length of magnetic circuit.

Note: The ratio $\frac{e_r}{E}$ is the value of voltage which appears across one-half of the reactor expressed in per cent of circuit voltage E. As this voltage is induced in both halves, the total voltage appearing across the entire reactor, is twice this value.

The curves show graphically the effectiveness of a small air gap in reducing the peak voltage. It is apparent from the curves that the peak voltage across the reactor can be limited to relatively small values by:

1. Designing reactor for relatively low flux densities.
2. Using air gap which is at least 1 per cent of the total length of the magnetic circuit.
3. Designing the reactor with large magnetizing current, so as to avoid excessive voltages when overload currents are flowing.
4. It is also apparent by comparing solid with dotted curves that voltage peaks are reduced by providing the transformer with a larger number of smaller percentage steps so that the reactor may be designed for a smaller fraction of circuit voltage.

Influence of Power Factor. These curves give peak values for zero power factor load, the condition under which the peaks are maximum. With increasing power factor, the peaks are reduced appreciably in value, on account of the fact that current zero is shifted away from the instant of maximum circuit voltage. Voltage peaks are approximately proportional to the reactive factor of the circuit. Thus for an 80 per cent power factor circuit, the peak voltage will be 60 per cent of the value given in the curves.

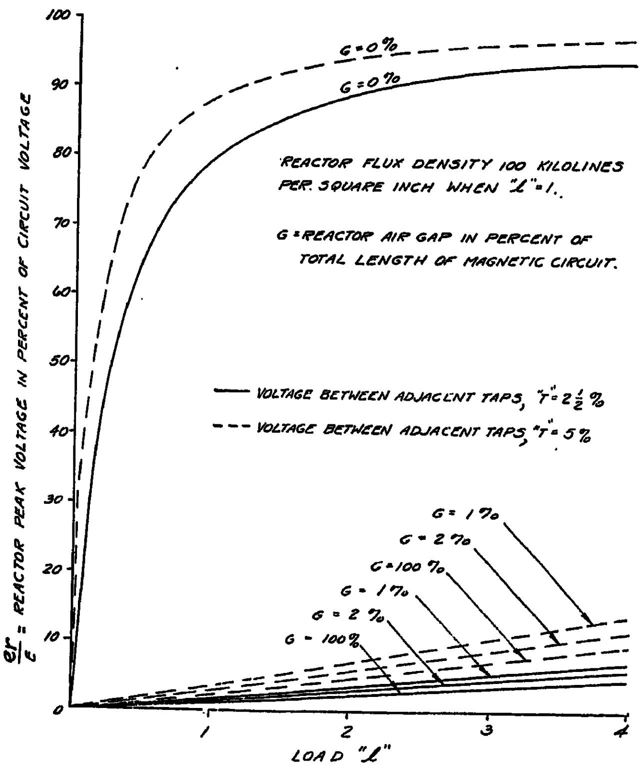


Fig. 3—Characteristic Curves of Series Reactors

Showing how very small air gaps greatly decrease the peak voltages induced in the reactor by magnetic saturation

Appendix

Effect of Magnetic Saturation in Reactors

Theoretical Determination

For the unsymmetrical position (Fig. 1) the division of circuit voltage E between the load and the reactor is given by equation (2). This equation holds for all instantaneous values of current voltage and inductance, and for any type of reactor. It is limited, however, to pure inductive loads.

$$\frac{e_r}{E} = \frac{L' \dfrac{di}{dt}}{L \dfrac{di}{dt} + L' \dfrac{di}{dt}} \tag{2}$$

where

e_r = voltage across one-half of reactor (instantaneous value)

E = circuit voltage (instantaneous value)

Since the equation holds for all instantaneous values it can be used to determine the maximum values, *i. e.*, the voltage at the instant when the current is passing through zero. Since in the unsymmetrical position, the reactor and load current are identical, di/dt is the same for both reactor and load, and may be canceled from the numerator and denominator of equation (2), which therefore simplifies to

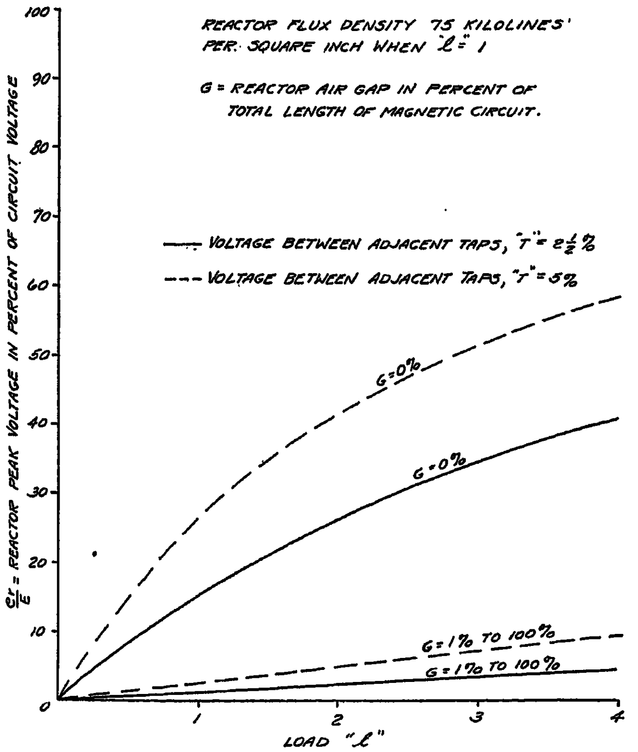


FIG. 4—CHARACTERISTIC CURVES OF SERIES REACTORS

Showing how very small air gaps greatly decrease the peak voltages induced in the reactor by magnetic saturation

$$\frac{e_r}{E} = \frac{L'}{L + L'} \tag{3}$$

Load inductance L is constant for a given load and varies approximately inversely as the value of the load. Let the inductance of the normal load be defined as the value of inductance corresponding to the load which has the same peak current in the unsymmetrical position as the magnetizing current of the reactor at its rated sine-wave voltage, $\dfrac{T}{2}$. (See Figs. 5 and 6.) This is a convenient assumption because it makes the peak magnetizing current in the bridging position equal to one-half of the normal load current. If the actual load current is l times what is assumed here as "normal" load current, then

$$L = L_0/l$$

Equation (3) may then be written

$$\frac{e_r}{E} = \frac{L}{\dfrac{L_0}{l} + L'}$$

Let the constant L_0' be the inductance of an air-core reactor so chosen that the division of voltage for normal current, between reactor and load is

$$\frac{e_r}{E} = \frac{L_0'}{L_0 + L_0'} = \frac{T/2}{(E - T/2) + T/2}$$

The magnetization curve of such a reactor is given by the straight line in Fig. 7. Let curve *II* in Fig. 7 be the actual magnetization current curve of the iron core reactor, having the same peak magnetizing current as the air core reactor, at its rated voltage $T/2$.

The instantaneous inductance L' of the iron core reactor and L_0' of the air core reactor will be in the ratio of the slopes of the two curves at the particular current value

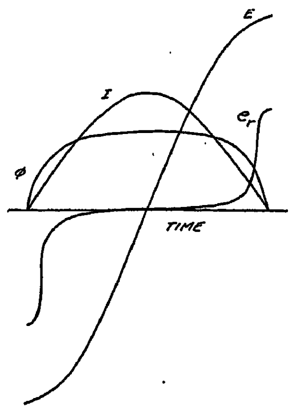


FIG. 5—VOLTAGE AND CURRENT RELATIONS IN REACTOR FOR UNSYMMETRICAL POSITION, FIG. 1, WITH NORMAL LOAD CURRENT. $l = 1$

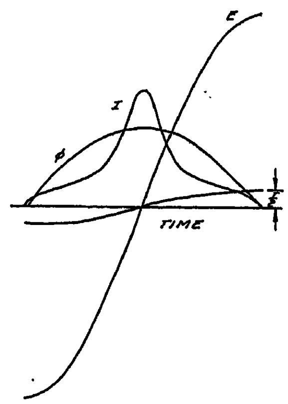


FIG. 6—VOLTAGE AND CURRENT RELATIONS IN REACTOR FOR BRIDGING POSITION, I. E., REACTOR CONNECTED ACROSS ADJACENT TAPS, WITH NORMAL MAGNETIZING CURRENT AND ZERO LOAD

E = Circuit voltage
e_r = Voltage across the reactor
T = Transformer tap voltage
I = Current through reactor
ϕ = Flux in reactor

$$\frac{L'}{L_0'} = \frac{\text{slope of curve } II}{\text{slope of curve } I} = r$$

Since our interest centers on the maximum voltage and the maximum voltages occur when the fluxes are passing through zero, therefore, to obtain the maximum reactor voltage, we should take the ratio of slopes at the

TABLE II

Maximum reactor flux density kilolines per sq. in.	Gap zero (all iron)	Values of r Gap 1% air	Gap 2% air	Gap 100% (all air)
0	1	1.00	1.00	1.00
20	6	1.00	1.00	
40	6	1.00	1.00	
60	7	1.00	1.00	
70	10	1.01	1.01	
75	14	1.01	1.01	
80	23	1.03	1.01	
85	50	1.07	1.03	
90	112	1.16	1.08	
95	207	1.31	1.15	
100	314	1.47	1.24	
105	488	1.74	1.37	
110	606	1.92	1.46	
115	829	2.25	1.64	
120	1,195	2.81	1.91	
125	2,380	4.61	2.80	
130	4,540	7.90	4.44	

origin. Table II gives this ratio for various values of normal flux density in the reactor, as determined from a typical d-c. magnetization curve of transformer steel for any maximum value of flux density.

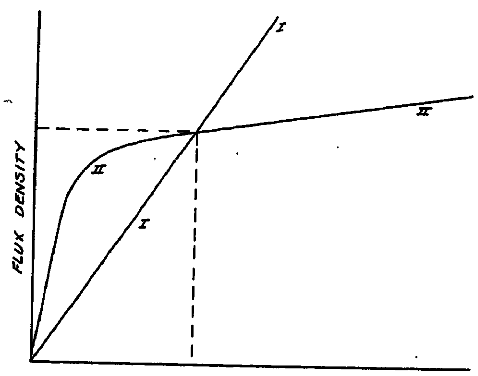


FIG. 7—COMPARATIVE MAGNETIZING CURRENT CURVES OF AIR CORE REACTOR (I) AND IRON CORE REACTOR (II) HAVING THE SAME NORMAL FLUX DENSITY

The general form of the equation giving the relation between peak reactor voltage, as a function of load and the permeability ratio r is

$$\frac{e_r}{E} = \frac{\dfrac{T}{2}\,r}{\dfrac{E - \dfrac{T}{2}}{l} + \dfrac{T}{2}\,r} \qquad (4)$$

where

T = voltage across adjacent taps
E = circuit voltage
l = load number
r = ratio of slopes on d-c. magnetization curve

Equation (4) is plotted in Fig. 3 and Fig. 4, in which e_r is the ordinate and l the abscissa.

Influence of Power Factor. Equation (4) is true for a zero power factor circuit. For other power factors, approximate values of voltage peaks may be obtained by multiplying equation (4) by the reactive factor of the circuit.

ACKNOWLEDGMENT

The author wishes to acknowledge the valuable suggestions given by Mr. A. Boyajian in connection with the theoretical development of the effect of magnetic saturation on voltage distortion, and also the assistance rendered by Mr. G. Heye in the numerical calculations and the plotting of the curves.

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Discussion

F. L. Snyder: Mr. Blume has demonstrated advantages to be derived from introducing a small air gap into the core of the reactor used in switching the load from one transformer tap to another. The paper deals with the method of tap changing described in papers which he has presented before the Institute heretofore.

It should be noted, however, that the introduction of an air gap into the core of the reactor increases its magnetizing current and consequently the duty on the transfer or load switches of the tap changer. This results because the switches must interrupt the vector sum of one-half the transformer load current and the reactor exciting current. For low-voltage circuits, this increase in current is not compensated for by the reduction in voltage. Furthermore, the point must not be lost sight of that some operating engineers prefer the method of tap changing using the position with the reactor spanning two taps, as an operating position. This is because fewer transformer taps are necessary, and a smaller number of points or contacts are required on the tap changer. When this simpler method of tap changing is used, the iron loss and exciting current of the reactor, which are added to that of the transformer on alternate positions, will be considerably greater with an air gap in the core of the reactor than when the core is not provided with such a gap.

I would like to supplement Mr. Blume's statement that the distortion of the current wave as it approaches and passes through zero is due to the saturation of the core. This distortion occurs only in case the voltage available in the circuit is not sufficiently high, with a sine wave current, to satisfy the fundamental law that the instantaneous voltage across the reactor is proportional to the rate of change of flux with respect to time. If the voltage available in the system at this instant is sufficient to satisfy the law with a sine wave current, no distortion will take place. This point is discussed by Messrs. Fahnoe and Maslin in their paper "Peak Voltages Across Saturating Reactances," published in the March 1932 issue of *The Electric Journal.*

Mr. Blume points out that the voltage across one-half of the reactor at the instant the current passes through zero, is dependent upon the power factor of the system, since this voltage can never exceed the instantaneous voltage available in the system. I would like to add that for tap changers used in a system for supplying a synchronous load, or used at a tie between two systems, the voltage across one-half the reactor is limited by the difference between the internal voltages at the two ends of the system. These two limitations of the voltage which can appear across one-half the reactor are of major importance, since, for practical applications, it is always the voltage available in the system at the instant the current passes through zero, and not the system voltage, that determines the voltage that may appear across the reactor. Mr. E. L. Harder has analyzed this quite thoroughly as it applies to polyphase as well as single-phase circuits, in his article "Peak Volages on Saturating Reactances," published in the March, 1932 issue of *The Electric Journal.*

It is my opinion that the value of the table giving the voltage across one-half the reactor would be enhanced if the load current were expressed as some constant value, rather than as a percentage of the exciting current of the reactor when spanning two adjacent taps. Changing the length of the air gap in the core of the reactor changes its exciting current and therefore changes the load current given in the table. This results in a different load current for each set of values. Furthermore, it should be noted that the voltages across one-half the reactor, given in the table, will be obtained only with the transformer supplying a pure reactive load with practically no external reactance. For normal loads, this voltage will be considerably less than the values given in the table. For example—applying equation 1 to a 25,000-kva., 72,000-volt, single-phase transformer equipped with load tap changer and reactor without an air gap in the core, which has been in service for several years, gives a value of $\frac{Er}{E}$ of 28.8 per cent when $L = 12$ and $T = 4$ and the power factor of the load $= 80$ per cent. It should be noted, therefore, that for actual applications, the value of $\frac{Er}{E}$ is in reality only about one-third of the theoretical value shown in the tables when the external resistance and reactance and power factor of the system are taken into consideration. Also, the measured voltage will, in every case, be less than the theoretical, calculated voltages, due to the fact that the space between the laminations of the core make up a small air gap, so that in reality, even the so-called solid core reactor has a small air gap.

In conclusion, I would like to point out that whether or not an air gap should be used in the core of the reactor depends upon the characteristics of the circuit which the designer wishes to secure, and that in any event, the tap changer, the transformer, and the reactor must be insulated for the voltages which may be impressed upon them under both normal and abnormal conditions. As pointed out in a paper "Tap Changing Transformers." published in the June, 1932 issue of *The Electric Journal*, the load tap changer should not only be capable of successful operation during normal conditions, but also under short-circuit conditions, since a tap changing operation may conceivably take place at the instant of line short circuit.

A. Boyajian: Attempts to limit a voltage rise by saturation result usually in just the opposite effect. Uncritical expectations based on rms. characteristics are brought to grief, and the very feature (saturation) depended upon for protection stings and pierces the insulation of the circuit by needle shaped voltage peaks.

Can saturation phenomena in an a-c. circuit be analyzed and understood physically in terms of elementary sine-wave concepts associated with linear circuits without recourse to advanced mathematics? It appears that this can be done, and it is very desirable for all technically inclined engineers to grasp it. The d-c. saturation curve of a closed iron core reactor may be represented with sufficient approximation by two straight lines meeting at a point designated by a current value I_t and flux density B_t, —transition values. For all values of current less than the transition value i_t, the reactor has a constant reactance X_1; and for all values of current above the transition value, the reactor has another constant reactance X_2. The wave shape of the behavior of the circuit then can be determined by ordinary sine-wave concepts, using X_1 during part of the cycle, and X_2 during the next, the beginning and ending of these parts or zones being determined by the transition current i_t. Adjoining zones are made to fit each other by elementary transient components, namely, by a d-c. transient, when capacitance is absent, and by a natural oscillation when capacitance is present.

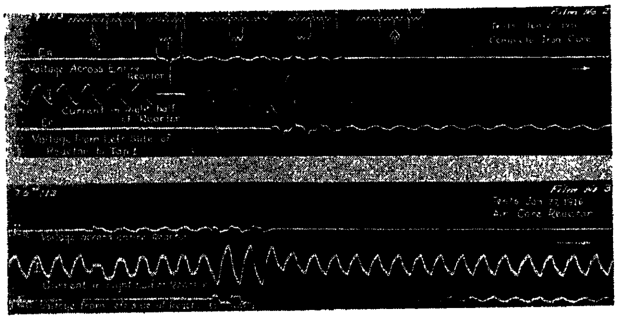

FIG. 1—OSCILLOGRAMS OF VOLTAGES ON PREVENTIVE REACTORS

This scheme of analysis is presented in considerable detail in an article in the *General Electric Review* for September and December 1931, with a number of illustrative examples. Strange wave shapes, which would have otherwise appeared most baffling for analysis, are found to consist of nothing but sections of two normal frequency sine-waves plus sections of two exponentially decaying d-c. transients. If capacitance is present, the damped d-c. transient is replaced by a damped oscillation at the natural frequency of the circuit. The physics of the phenomena is clarified by such a conception and analysis; and, in most instances, the final answers, that is, the equations of current and voltage, can be written down by inspection.

H. O. Stephens: In some of the early schemes for changing transformer taps under load split blade dial switches or straight line switches were used. Preventive reactors were connected between the split blades or contacts so that when the blades bridged adjacent taps during the transition periods the circulating current between the taps would be limited to safe values. It was observed that if these reactors were wound on completely closed magnetic circuits the arcing on the contacts was severe. Accordingly, tests were made at Pittsfield, Mass. in 1916 to determine the relative merits of preventive reactors, first with completely closed magnetic circuits, second with cores having air gaps and third with air core reactors.

These tests showed that when preventive reactors with closed magnetic circuits were used, decided peaks in the voltage waves

across the reactors were obtained, the arcing on the contacts was severe and the contact life unsatisfactory. With air core reactors or with iron core reactors with suitable air gaps in the core so that substantially a straight line volt-ampere characteristic throughout the working range was obtained, the bad peaks in the voltage across the reactor were eliminated and the life of the contacts greatly increased. Comparative oscillograms taken during these tests show the marked superiority of the air core reactor over the closed iron core reactor (Fig. 1).

Since those tests in 1916 it has always been our policy at Pittsfield to recommend only reactors having substantially straight line volt-ampere characteristics throughout their working range when used as preventive reactors for transformer tap changing under load.

Frequently the preventive reactance is obtained by a suitable arrangement of the windings of the transformer itself in which case the volt-ampere characteristic of the preventive reactance is a straight line.

In the *General Electric Review* for December 1931, Mr. Boyajian gave a method of analyzing such non-linear function as the volt-ampere characteristic curve of iron core reactors with closed magnetic circuits. Mr. Blume's paper gives a simple conception whereby it is possible readily to determine the proper characteristics of preventive reactors and to determine quantitatively the effectiveness of gaps in cores and thereby avoid the hazards of peaked voltages across reactors and contactors when used for changing taps on transformers under load.

L. F. Blume: The primary purpose of the paper was to derive and express in mathematical language, the fundamental effect of magnetic saturation in tap changing devices and to give a simple means by which the maximum value of the peak voltage induced in a circuit can be easily determined for specified conditions. It is appropriate for Mr. Snyder to call attention to the fact that these voltages are very much affected by a variety of circuit conditions not considered in the paper. In addition to those which Mr. Snyder has mentioned, the circuit consisting of a parallel transformer bank, or the presence of line capacitance, will very materially modify the values of peak voltages given in the paper. Although it is admitted that the subject is not complete without considering these effects, nevertheless I cannot agree with Mr. Snyder in his apparent conclusion that such circuit conditions can be relied upon for the purpose of preventing or greatly reducing the intensity of the peaks. A transformer designer cannot be sure that his transformer will always be operated with special circuit conditions, and at least a transformer provided with a tap changing device, should be capable of operating under just as great a variety of conditions as an ordinary transformer. In other words, the fact that the tap changer is added to the circuit should not constitute a restriction of the conditions under which the transformer bank can be safely operated. The paper assumes that it is sufficient to derive a practical equation whereby the maximum values under the worst condition of service operation can readily be derived.

It is unfortunate that Mr. Snyder in the example in which he obtains a value of 28.8 per cent for voltage peak, fails to give all the conditions necessary under which this value was obtained. In addition to the constants which he gives, it is necessary to know the ratio of load current to normal reactor magnetizing current and the value of r, which measures the inductance of the reactor at the instant of current zero in terms of its normal inductance. To obtain the value for maximum peak voltage of only 28.8 per cent without using an air gap and assuming power factor of load equal to 80 per cent involves, according to equation (4) of my paper, restricting the normal flux density in the reactor and also the load current in terms of reactor magnetizing current, to rather small values. For example, let us assume that the normal maximum density in the iron of the reactor, that is the maximum density of the reactor when connected across adjacent taps, is 85 kilolines per square inch. From Table II the value of r corresponding is 50. Substituting this value together with the constants which Mr. Snyder assumes in equation (4) and equating to 28.8 per cent, with proper correction for the power factor of the load, results in a value of l approximately equal to unity. This means that the example is restricted to a load current not exceeding the normal magnetizing current of the reactor. As a primary purpose of avoiding air gaps in the reactor has been to reduce the exciting current to inappreciable values, as compared with the normal load current on the transformer, the conclusion follows that the example which Mr. Snyder cites applies only when the load on the transformer is a very small fraction of the rated load. Accordingly, I do not see any evidence whatever for the conclusion which Mr. Snyder draws that in practise the actual values of these peaks will be reduced to one-third of the theoretical values. Furthermore, the paper which Mr. Snyder refers to and which was published in the *Electric Journal* in March 1932, contains equations for calculating the peak voltages under conditions similar to those described in the present paper, and apparently there is no substantial difference between them. In this paper the specific statement is made that the equations given, although theoretically not precise, nevertheless will give substantially the correct values. I cannot understand the statement made by Mr. Snyder as follows: "Furthermore, it should be noted that the voltages across one-half the reactor given in the table will be obtained only with a transformer supplying a pure reactive load with practically no external reactance," unless Mr. Snyder meant to use the word "resistance" for the last word in this sentence instead of "reactance."

I am glad that Mr. Snyder has called attention to the possibility that a tap changing transformer may conceivably be called upon to operate under very heavy overloads, or under overloads approaching dead short circuit, and it is desirable that under this condition no harm come to either the transformer or the circuit upon which it is operating. Under such conditions, the impedance of the connected load is relatively low and almost entirely reactive. From the standpoint of the values of the peak voltages across the reactor, this condition is about the most severe that can be imagined, because, first, the ratio of unsaturated reactor constant to the reactance of the remainder of the circuit increases with the decrease of load inductance so that under short circuit, this ratio is maximum; and, second, short-circuit currents are generally of very low power factor, so that the peak voltage appears practically at the instant of the maximum circuit voltage. The effectiveness in reducing these peak voltages of an appreciable air gap, together with designing the reactor for a magnetizing current comparable to the rated current, is made evident by examining the curves given in Fig. 3 and Fig. 4. Assume, for example, that heavy short circuit will correspond to a value of l plotted on the horizontal scale equal to about 10. It is evident from these curves that any attempt to reduce greatly the reactor magnetizing current, or of eliminating the air gap, means that when the transformer is called upon to change a tap with a short circuit on the system, peak voltages will be induced across the reactor terminals practically equal to double circuit voltage.

Influence on Commutation of Brush Contact Drop

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I. INTRODUCTION

IN designing electrical commutating machinery, an attempt is usually made to produce a linear change of current with time during commutation. In this case the current density under the brush is uniform, and therefore the voltage drop at the contact between brush and commutator will also be uniform over the brush surface. It is well known, however, that straight-line commutation[1] is rarely achieved. Furthermore, there is some doubt as to whether straight-line commutation is the most desirable form. In the case of non-linear commutation the current density is not constant across the brush surface, and consequently the contact drop will not be constant. This means that calculations made to determine the change in current in a commutating coil will be greatly in error if constant contact drop is assumed. Another difficulty is introduced by the fact that the contact drop will change with time in any small area on the brush surface, and therefore the static curve between voltage and current measured at the brush contact cannot be used and the transient characteristics of the brush contact drop must be known.

The usual lack of consideration of the nature of contact drop in dealing with commutation problems leads to the result that many observed phenomena cannot be explained by means of the calculation made. For example, the classical theory of commutation can in no way explain sparking underneath the brush, peculiarities found in brush and commutator wear, the choice of certain brushes in order to obtain good commutation, etc.

II. THEORY OF A SLIDING CONTACT

The electrical nature of a sliding contact is externally expressed if a volt-ampere characteristic of the contact is given. In the case of a graphite brush and a copper ring or commutator, the general form of the volt-ampere characteristic is well known, and the static characteristic is given as curve *a*, Fig. 1. There is evidence that this characteristic decrease in resistance of a sliding contact with increasing current may be explained on a thermal basis. Slepian[2] gives a formula

$$\left(T = \frac{E^2}{33.5\, K\, \rho} \right) \qquad (1)$$

for the temperature of a small current carrying contact area between two materials. He also cites tests in which contact drop is determined as a function of the specific resistance of the materials involved. Since a curve plotted between the logarithm of these two quantities is a straight line having a slope of 0.43, an exponential law is indicated.

To check the relation between contact drop and the resistivity of the brush material, a test was arranged in which a number of brushes, each of a different resistivity, and each carrying the same current, could be run simultaneously on the same copper slip-ring. By sanding the ring with fine sand paper each time shortly before taking a set of readings, very nice results could be obtained as shown by the curve of Fig. 2. The contact drop obtained on the freshly sanded ring might be called the primary contact drop for it has to do with the fundamental process by which current is conducted across a sliding contact. The difference between this drop and that obtained after a polished film has formed on the commutator and brush might be called the secondary contact drop for it depends upon how the brush polishes and how it rides on the polished surface of the commutator.

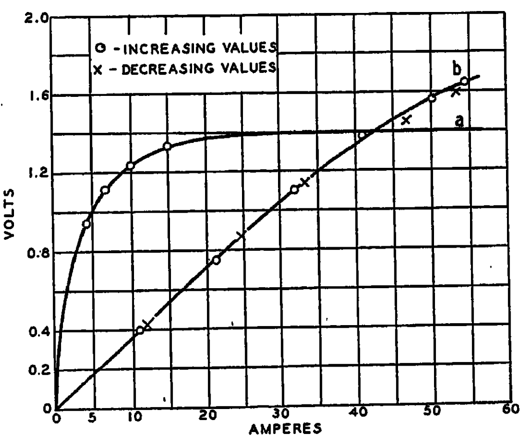

FIG. 1—STATIC AND TRANSIENT BRUSH DROP CURVES

Fig. 2 shows that the relation between the square of the contact drop and the resistivity of the brush material is nicely approximated by a straight line. Neglecting the difference in thermal conductivities of the different brush grades, this curve suggests that the contact points in all copper-carbon sliding contacts

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1. *Commutation Considered as a Switching Phenomena,* by R. E. Hellmund and L. R. Ludwig, A.I.E.E. Winter Convention, 1932.

2. *Temperature of a Contact,* by J. Slepian, A.I.E.E. JL., October 1926.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

operate at approximately the same temperature. It further shows a very definite relation between the resistivity of a brush and its contact drop. This proves definitely that the contact drop is not produced, as is sometimes thought, by the current flowing uniformly through a thin layer of some high resistance material. The results of this test thus check further the hypothesis suggested by Slepian.

R. Holm[3] has shown that with stationary contacts the current is not carried across the entire contact area, but that it is carried through a relatively small number of points at which the contact is intimate. He describes the condition by speaking of "sieve resistance" at the contact surface. This condition is also true with sliding contacts, as later calculations and experimental results will show. Hence it may be said that the current is carried through small portions of the total brush surface at a comparatively small number of discrete points. Since the contact drop is a function of the resistivity of the brush material, the contact drop is not actually a difference in potential between contact points on the brush and on the ring or commutator, but is really a

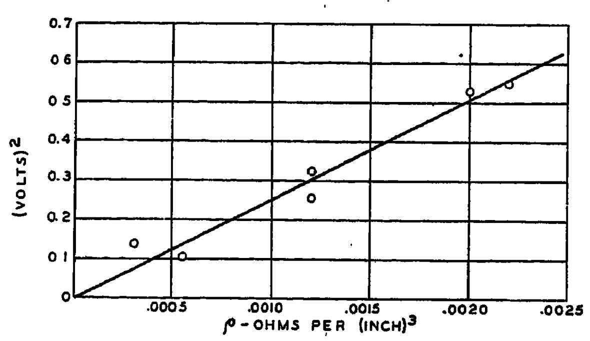


FIG. 2—CURVE OF BRUSH RESISTANCE AND SQUARE OF CONTACT DROP

voltage drop in the brush itself due to the fact that the current density at the contact points is extremely high and that the brush material has considerable resistivity. In other words, the contact drop is merely a resistance drop near the surface of the brush. The volt-ampere characteristic previously referred to may then be explained as follows:

If the current through the brush is increased, it will in turn tend to increase the temperature of the contact points, and whatever conditions exist at the surface which prevent complete intimate contact will be altered in such a way as to allow a greater total area of contact between the brush and the slip-ring or commutator, and consequently a lower resistance of the total contact.

The formula for the temperature of a contact point given by Slepian is derived for a contact between two electrodes of like material. In this case half the electrical drop occurs in each of the electrodes and the maximum temperature as expressed by the formula occurs at the point of contact. In the contact between a brush and a commutator substantially all the electrical drop occurs in the relatively high resistance brush, as just shown. The actual area of contact of the brush with the commutator must remain at the temperature of the commutator and will therefore have no temperature rise. The maximum temperature in this case is found to be the same as that given by Slepian's formula, but this maximum temperature occurs, not at the point of contact, but in a region of the brush very close to the point of contact.

Intimate contact at all points between the brush and ring is prevented by some form of film. The film must have properties such that if the temperature at a given contact point is increased, it will be driven back, thus allowing a somewhat greater area of actual contact. A film of adsorbed gas on the surface of the brush will have the required properties, for example, in that such a film would prevent close contact between brush and ring and at a certain temperature would be driven off, thereby allowing a greater contact area. The film may also be one of copper-oxide, or a uniform film of graphite material. It should be noted that in either case there is no stable equilibrium during operation; in other words, if a contact is operating with uniform current density and uniform temperature over the entire area, any slight increase of temperature at some point of this area will lower the resistivity at this point, so that very soon the current would not be uniformly conducted, but would again be carried at discrete points.

Tests by Baker[4] in hydrogen and nitrogen did not give contact drops appreciably different from those obtained in the air, and it seems therefore that the film is not in the nature of an oxide.

III. THE MECHANICAL NATURE OF THE SLIDING CONTACT

When a graphite brush runs on a copper ring or commutator which is smooth, in such a way that the mechanical conditions are good, the surfaces are found to have a high state of polish. This polishing, as described, for example, by Adam,[5] results in an amorphous layer of material on the brush and commutator surfaces. In fact, the polishing is so complete that the brush surface often resembles a mirror, and if a straight edge is placed across it a straight reflection is obtained on the surface. Thus, it would be expected that the number of contact points would be comparatively large in case these points are due to coincidence between the surfaces. As pointed out by Lamme,[6] material seems to be transferred across the contact and deposited on the opposite surface, the direction of transfer being the same as the direction of the current. The nature of this action is probably due to the formation and the de-

3. *Zeit. für Tech. Physik*, 1928, p. 454.

4. *Electric Journal*, Feb. 1932.

5. Adam "Physics and Chemistry of Surfaces," 1930, Clarendon Press, Oxford.

6. Lamme "Electrical Engineering Papers," W. E. & Mfg. Co., E. Pgh., Pa., 1919.

struction of small bridges between the materials, and may be somewhat as described by R. Holm[7] in the case of stationary contacts. The voltage required to build such bridges as given by Holm, is of the same magnitude as that of the contact drop. It is probable that the polishing action is considerably assisted by the flow of current and the deposition of material.

It is interesting to note that the frictional loss is less when current is passing through the contact than otherwise. It may be supposed that this is due to the decreased coefficient of friction resulting because of the better polishing. The current flow is important to the polishing action as it provides a means for transfer of material and thus for a greater smoothness of the surfaces. Thus it is often found that when current is first applied to a contact even after it is well worn in, there will be a slow decrease in contact drop and at the same time a greater regularity in voltage regulations will be found. The time required for the contact to reach the steady state is comparatively long, in fact, too long to be accounted for by variations in temperature of the contact points themselves. It is more probable that a large number of contact points will be present after the polishing has been well established.

IV. Dimensions of a Contact

On the assumption that a point contact area between a brush and commutator is circular in shape it is possible to calculate the product of the number of contact points N and the radius of a contact area α. The derivation of Appendix I shows this product to be

$$N\alpha = \frac{\rho I}{2\pi E} \tag{2}$$

where ρ is the electrical resistivity of the brush material, I is the total current through the contact and E is the voltage drop across the contact. Thus if either the number of contact areas or the radius of a contact is known, the other can be determined.

Little[8] has made some tests to determine the number of points of contact under a brush by discharging a condenser across the contact. The current during the discharge was sufficient to burn the ring and brush at the contact points. Following the discharge the ring was stopped and the number of contact points was counted. These tests probably give correct results because the current increase is so rapid that the contact resistance does not have time to change and hence the drop becomes so high that a small arc is formed.

Evidence was found that the number of contact points varied from ten to more than fifty. With this data it is possible to determine the size of a contact point necessary to account for the voltage drop observed.

Assume a brush with the following specification:

$$N = 30 \text{ points}$$
$$I = 50 \text{ amperes}$$
$$\rho = 0.005 \text{ ohms per cu. cm.}$$
$$E = 1.00 \text{ volts}$$

Substituting in equation (2)

$$\alpha = 0.00133 \text{ cm.}$$

If the number of contact points is reduced to three,

$$\alpha = 0.0133 \text{ cm.}$$

Even for the small number of larger points the calculated current density has the enormous value of 29,900 amperes per sq. cm. although as will be shown shortly, this value is quite feasible.

To test the feasibility of carrying very high current densities in a small contact, the face of a commercial sized brush was cut away very slightly to leave a small raised point 0.0013 sq. cm. in area in the center of the brush face to make contact with the slip-ring. It was found possible to raise the current density in this small contact to about 14,000 amperes per sq. cm. before any evidence of distress was observed. The volt-ampere characteristic of this small contact was similar in shape to that observed on a large contact and it must therefore be concluded that even this small contact still contains a number of separate and distinct smaller contact points just as the large contact does. Thus it becomes feasible to believe that an actual point of contact might very well carry a current density of 50,000 or even 100,000 amperes per sq. cm.

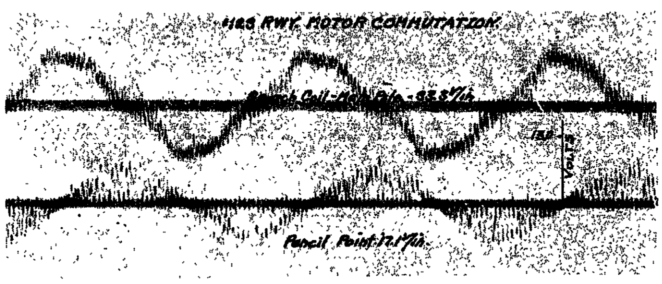


Fig. 3—Brush Drop Oscillograms

If a positive and a negative brush are both running on a slip-ring, the initial contact drop at both will be found to be the same shortly after voltage is first impressed. This is because the number of contact points is probably the same and the size must therefore be the same. This result has been observed when using direct currents, and furthermore the drop taken on a-c. machines is found to be the same with either direction of current through the brush, Fig. 3. After a short period of operation with direct current, however, the drop at one brush is found to become larger than at the other. This difference can only come about if the number of points on one brush becomes greater for some reason. The probable reason is that the difference in material transferred at the two polarities results in different degrees of smoothness. An increase in the number of contact points reduces the current to be carried per contact and thereby reduces the contact drop.

7. *Wiss. Ver. aus dem Siemens-Konzern*, X Vol. 4 Heft.
8. A.I.E.E. Trans., Vol. 50, No. 2, 1931, p. 718.

V. Transient Brush Drop

It has been found experimentally that in case the current is rapidly increased through a contact, a volt-ampere curve will be obtained shown as curve *b* in Fig. 1. This curve corresponds to an almost constant contact resistance and indicates that the contact does not have time in which to adjust itself to the higher value of current, as the current is continually increased. Since the change in resistance is due to a thermal phenomenon, the time lag which exists in the contact must also be thermal, and is, in fact, due to the time required to raise the temperature of the contact point. There is also the possibility, of course, that there is some time delay in altering the nature of the contact surface even after sufficient temperature has been reached. For example, after an adsorbed gas film is considered to be present some time is required to drive off this film and thus allow a greater area of contact. However, calculations (not given) show that any time lag due to this or a similar phenomenon must necessarily be quite short. Calculations are made in the Appendix to determine the rate of heating of the contact points. The following equation may be used for this purpose:

$$\frac{\partial T}{\partial t} = \frac{E^2}{67.3\ \gamma \alpha^2} \tag{3}$$

where γ is the specific heat of the brush material in calories per cu. cm., and T is the temperature rise of the contact in degrees centigrade. Such a calculation assumes that the contact point does not move on the brush during the heating. This assumption may be justified by the fact that no motion of the contact points would be expected to take place until the particular point had worn down, and this would require more time than the time necessary to heat the point.

The result is obtained that a point having the dimensions given in Section IV ($\alpha = 0.0133$ cm.) would require 0.032 sec. for heating to 62 per cent of its final temperature.

It is interesting to note from equation (3) that the rate of heating of a contact point depends on the properties of the brush and, of course, on the size of the contact point. This fact may open the door to the reasons which underlie the successful use of certain brushes under certain commutating conditions. A further discussion of this factor will be given in the next section.

VI. Effect of Transient Brush Drop on Commutation

The current density under a brush varies from point to point, depending upon the voltage induced in a coil and the position of the associated bars under the brush. Except with straight-line commutation, there will be rapid changes in density at any point of the brush face; these changes occurring at commutator bar frequency. Conditions may be very severe in case of more than one coil per slot, because the curve along which the current changes for two consecutive coils may vary widely.

If such changes in density occur in practise, the voltage between a portion of the brush contact and the commutator becomes very high, and consequently, sparking under the brush will result. In Fig. 3 an oscillogram is shown of the voltage from the brush to a point on the commutator and it may be seen that a potential difference as great as 15 volts is reached. Such a potential difference is well above that required for the maintenance of a spark in air, which may require about 11 volts. Hence, in considering sparking during commutation, two kinds must be differentiated; first, sparking underneath the brush due to high transient voltages, and, second, the usual trailing edge sparking. The first form must not be confused with sparking due to mechanical roughness of the commutator.

In order to obtain good commutator and brush life, it is very important to avoid sparking under the brushes, which may occur even in the absence of the trailing edge sparking. An obvious way to avoid this difficulty is to design the machine so that no radical changes in density will take place. However, this cannot always be accomplished, in which event the designer often experiments with various grades of brushes and frequently finds one which operates satisfactorily. The reasons for the success of some brushes and the failure of others have not always been apparent. In these cases the explanation may be found in the fact that the successful brush has a very large number of contact points, and thus points of small area, which will heat and cool with sufficient rapidity so that high transient voltages will be avoided.

Another puzzling question in connection with commutation is that of why the current density in brushes must be kept so low when it is known that a much greater density may be employed in the laboratory without sparking. For example, a figure of 50 to 70 amperes per square inch is a fair design value, whereas densities of several thousand amperes per square inch have been used without sparking during laboratory tests. This matter is very important when it is realized that even doubling present densities would have the length of present commutators. In Section IV it was shown that the rate of heating of the contact points depends upon their size, which is a function of the current density. It is essential to keep the contact points small if sparking under the brushes is to be avoided, and therefore the real limitation of operating density becomes apparent as due to the necessity for keeping the current per contact small. In order to increase the present operating density, it would be necessary to make a brush which would operate at a higher density with small contact areas. This might be accomplished by making a brush having a very large number of contact points, or by greatly increasing the thermal conductivity without altering the electrical resistivity appreciably.

Appendix I

CALCULATION OF SIZE AND NUMBER OF CONTACT POINTS

The loss in a hemispherical shell of brush material around a point of contact is*

$$8\,\pi \times 0.0595\,\frac{E^2}{\rho}\,\frac{\alpha^2}{r^2}\,dr \text{ calories per sec.} \qquad (1)$$

E = volts drop in contact
α = radius of contact area in cm.
ρ = resistivity of brush material, ohms per cu. cm.
r = distance from point of contact.

The total loss for N points of contact is therefore

$$N \int_{\alpha}^{\infty} 8\,\pi \times 0.0595\,\frac{E^2}{\rho}\,\frac{\alpha^2}{r^2}\,dr \qquad (2)$$

$$= 8\,\pi \times 0.0595\,\frac{E^2 \alpha N}{\rho} \text{ cal. per sec.} \qquad (3)$$

This must also equal

$$\frac{1}{4.19}\,EI \qquad (4)$$

where I is the total current carried by the contact. Therefore

$$\frac{1}{4.19}\,EI = 8\,\pi \times 0.0595\,\frac{E^2 \alpha N}{\rho} \qquad (5)$$

or

$$N\alpha = \frac{\rho I}{2\,\pi E} \qquad (6)$$

Appendix II

RATE OF HEATING OF CONTACT POINTS

The heat generated per unit volume of the brush is*

$$\frac{\partial H}{\partial t} = 4 \times 0.0595\,\frac{E^2}{\rho}\,\frac{\alpha^2}{r^4} \qquad (7)$$

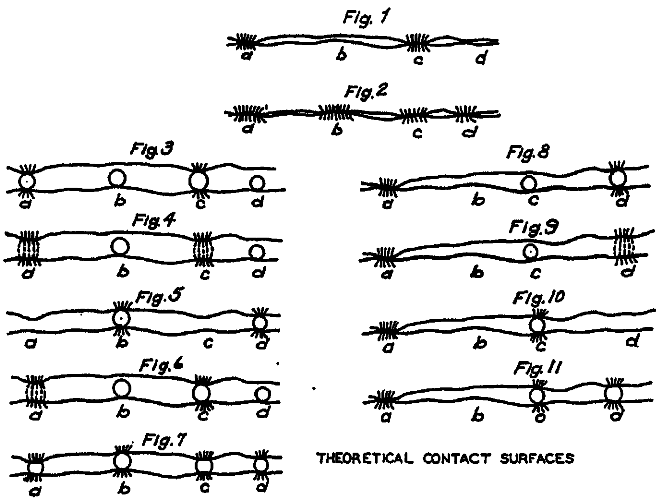
If γ is the specific heat of the brush material in cal. per deg. cent. per cu. cm., the initial rate of temperature rise at the point of maximum temperature ($r = 2a$) is

$$\frac{\partial T}{\partial t} = \frac{1}{\gamma}\,\frac{\partial H}{\partial t} = \frac{E^2}{67.3\,\gamma\alpha^2} \text{ deg. cent. per sec.}$$

Discussion

R. E. Hellmund: Contact phenomena and the characteristics of contacts under various conditions have been puzzling to electrical engineers for a great many years. While even yet a great many questions remain to be answered, considerable progress has been made in explaining these phenomena, and the paper presented by Messrs. Ludwig and Baker is a valuable contribution in this direction. It is especially interesting to note that while it frequently had been assumed that contact phenomena might require for their explanation entirely new and unknown basic principles, it seems now as though they might eventually be explained in a rather simple manner by assuming certain mechanical conditions of the contact areas and nothing but ohmic resistance in the materials proper and other well-known phenomena.

The theory discussed in the paper can possibly be illustrated by Figs. 1 and 2. If we have two irregular contact surfaces establishing small points of contact at a and c, as shown in Fig. 1, the drop is essentially caused by the ohmic resistance of the two materials in the neighborhood of the contact points. If the current suddenly increases before any change in this mechanical condition is possible, the resistance remains the same but the ohmic drop increases with the current, as indicated by curve 1b in the paper. If the increased current persists, it may be assumed that the heating of the small contact points increases to an extent which permits a certain disintegration of the materials at these points. This may result not only in increased contact surfaces at a and c as indicated in Fig. 2, but also in the establishing of additional points as shown at b and d, which would of course be possible if the carbon surfaces at a and c wear down a certain amount. This readily explains why with sustained load the resistance may decrease, keeping a fairly constant voltage drop. However, with this condition established and the current subsequently decreasing, it is not so readily seen why the resistance should again increase, as is found to be the case in practise. The assumption of the reforming of certain oxide and gaseous filaments with light loads, which would interrupt the circuits at some of the points of contact, would be necessary. With moving contacts there is nothing definitely eliminating such possibility because the high points on the commutator are continuously moving out of contact with the high points of the carbon, and it is quite possible that when contact with other high points on the brush is re-established, a film has been formed in many cases which will not be broken down except under certain conditions. In other words, even though many points of contact may have been established during operation with large current density, they do not necessarily continue to exist because of the motion of the commutator.



THEORETICAL CONTACT SURFACES

Instead of assuming direct contact between the two surfaces, another theory which assumes the existence of small loose particles between the surfaces, as shown in Fig. 2, might be advanced. The fact that such loose particles play an important part in the contact phenomena finds some support in the fact that both contact resistance and chattering noises can be materially changed merely by wiping the commutator surface with a dry piece of cloth. The assumption of the existence of such particles leads

*See reference 2.

to some rather interesting possibilities. Let us start out again with current conduction at *a* and *c* on account of the larger size of the particles located there, while at *b* and *d* there is no contact, as shown in Fig. 3. If we assume now that the current suddenly increases up to a certain value, the resistance may not change, but voltage drop increases in proportion to the current. On the other hand, if the current is suddenly increased to a much greater extent, it can readily be imagined that the particles at *a* and *c* explode and evaporate and that, as shown in Fig. 4, there is temporarily no contact at all but an arc at the points *a* and *c*. This in turn would mean that there would be not only the ohmic drop in the materials near the points of the arc but also an arc voltage. This might at times explain the arcing which is noted under the brush. Soon after the arcs have formed, but not until the brush pressure has been able to accelerate the mass of the brush, we will obtain the condition in Fig. 5, where the current will now be conducted through the particles at *b* and *d* and the arc extinguished at *a* and *c* due to the fact that the ohmic drop through *b* and *d* is now below a value which would sustain an arc. The condition in Fig. 4 would of course mean a rather appreciable voltage drop.

Instead of both particles at *a* and *c* vaporizing at the same instant, a condition as shown in Fig. 6 can be imagined. In this case it is assumed that the particle at *a*, on account of its smaller size, vaporizes before the particle at *c*. This would mean that temporarily all of the current would go through *c*, which of course would increase the ohmic resistance and result in a voltage-drop increase greater than in proportion to the current. This in turn would subsequently be likely also to vaporize the particle at *c*, but it is quite conceivable that in the meantime other contacts such as at *b* or *d* may be established. This previous hypothesis simply indicates that with a sudden increase in current, it is conceivable that we will obtain voltages anywhere between the initial voltage and an arc voltage. In the case of a slowly increasing current, conditions as in Fig. 7 are likely to prevail; namely, that the surfaces *a* and *c* (both of the electrodes and the interposed particles) disintegrate or wear and thus permit additional contacts at *b* and *d*, leading to a decrease of resistance with gradually increasing load. The assumption of interposed particles made in Figs. 3 to 7 of course makes it easy to explain the increase of resistance with decrease in load because, due to the motion of the commutator, there is a continuous change and introduction of new particles. This means that only a limited number of the larger particles will establish contact unless thay are either vaporized by sudden current increase or worn down by gradual increase, as the case may be.

Instead of having conditions as shown in Figs. 1 and 2 or those in Figs. 3 to 7, it is also quite possible that there are points of direct contact and points establishing indirect contact through interposing particles, as shown in Figs. 8 to 11. Fig. 8 shows the initial condition with direct contact at *a* and contact through a particle at *d*. Fig. 9 shows a case of material and sudden current increase vaporizing the particles at *d*. Fig. 10 shows the conditions slightly later after the carbon has had time to move and establish a new contact at *c*. Fig. 11 shows a gradually increased load permitting wear at *d*, and the consequent establishing of a new contact at *c*.

No claim is made that the above hypothesis has as yet been exhaustively checked with the results of experimental data, but it seems that there is nothing generally known which contradicts these possibilities. It may further be pointed out that the hypothesis advanced in connection with Figs. 3 to 6 assumes a certain motion of the carbons. This, if present, may lead to vibration and chattering, which in turn may bring about other conditions not discussed here in detail. Similarly, any roughness of the surfaces proper may lead to conditions which are not covered in this brief discussion. Further work along this line is very worth while, not only from a hypothetical and theoretical point of view but also because it is probable that great advances will not be made in the manufacture of contact materials until the contact phenomena are fully explained. In carrying out such work, it may be well to realize that possibly the ordinary oscillograms may not be fast enough for recording the maximum voltages for some of the transient conditions.

L. A. Heath: An instance of the ever changing conditions of contact between brush and commutator is that of brushes sparking when a cold rotary or generator is started and full load is carried immediately. Sparking at the brushes lasts for a period of say twenty minutes and then perfectly black commutation occurs and remains so for the balance of the run. This situation repeats every time the unit is started cold. During the initial period when sparking occurs the slope of the brush contact curve indicates too great an interpole field strength but after the sparking has ceased the contact curve is quite normal. The contact faces of the brushes when inspected during the first twenty minutes of operation, indicate that the brushes have changed their seating from that taken at the last shut down.

The question of an air film between brush and commutator or ring still presents a problem to be investigated thoroughly. In actual practise attempts are made to correct this fault by cutting slots in the faces of the brushes or drilling holes through the length of the brushes. Films or coatings on the collector surfaces may be formed in many ways, either by chemical fumes, oil or moisture in the air. Chemical fumes in sufficient concentration will form a film so heavy as to upset entirely the normal current collection and vicious sparking results. Also certain types of brushes will in due time absorb chemical fumes which destroy forever their customary current collecting properties.

During recent years the amount of moisture in the air also has been a factor in a number of brush operation problems. Just how great a part moisture plays in brush operation I am not prepared to say at this time. It has changed the friction losses considerably in a number of instances and has also altered the amount of the contact drop. At the present time there is under observation a brush test on a vacuum cleaner of a design such that the air is drawn across the motor. A record extending over several weeks shows that the color of the commutator and the degree of sparking vary with the relative humidity.

In part III of the paper reference is made to the desirability of a high polish on the contact faces of brushes. From observation in the field we have found that a high polish generally produces a higher friction and poorer commutation than a face slightly dull and pin pricked. Very often this high polish is produced when the machine is running at light loads and the current density is not great enough to cause a transference of brush material.

W. E. Stine: The "theory of a sliding contact" and data submitted by Messrs. Ludwig and Baker are in very close conformity with a theory which I advanced several years ago* to explain brush contact drop characteristics. I did not have any data as to the number of points in contact at any one instant of time but assumed that in all probability there were never less than three. It now seems that there are never less than ten points in contact.

The authors have not given us a detailed description of the kind of brush material or apparatus used; therefore there are a few questions raised in the following and a few points in which I express a different view.

Did the authors distinguish between brushes made of amorphous or electrographic carbon which have symmetrical specific resistance, and brushes made of graphitic carbon whose specific resistance measured in one direction may be many times greater than the specific resistance measured at right angles to that direction? Losses in the latter class of material cannot be calculated on the basis of hemispherical shells.

It seems that the authors have neglected the heat produced by friction when considering the temperature of the point of contact.

*"Brushes for Electric Motors and Generators," *Jl. of the American Society of Naval Engineers*, May 1925.

If we consider that one-half of the friction loss appears as heat in these minute points of contact, will not the temperature of these points be considerably higher than the temperatures indicated by the formula?

Since carbon has an appreciable negative temperature coefficient of resistance, will not the resistivity of the brush material at the point of contact be a variable?

I do not believe that the authors are correct in assuming that the actual area of contact of the brush with the commutator must remain at the temperature of the commutator. If this were true a brake shoe would never have a higher temperature than the wheel upon which it is bearing.

It has been my observation that the friction loss is less when carrying current only when the brush is permitted to deposit a film of carbon on the ring of commutator. If the brush has sufficient abrasive action to keep the ring or commutator clean and bright, the flow of current does not cause a decrease in friction.

From my experience I cannot agree with the authors' observations as to the behavior of brushes that develop a higher contact resistance at one polarity than at the other. Some grades of brush material have a greater tendency to do this than others. If we take a set of brushes that have this as a marked characteristic, place them on a copper ring, pass alternating current through them and connect an average value meter across a brush contact, we will find that a reading is obtained, indicating that the contact drop during one-half cycle is greater than during the other half. This is obtained only while the ring is moving. As soon as the ring comes to rest the meter returns to zero or nearly so.

Brush material having the greatest tendency to deposit carbon on the ring shows the greatest difference in contact resistance at the negative and positive contacts respectively.

My observation of this phenomenon has led me to believe that the higher contact resistance at the negative (motor) brush is due to the fact that at this contact the brush material disintegrates at a greater rate than at the other contact and as it is carried from under the brush it lifts the brush from the ring causing the current to pass through these loose particles of brush material and thus introduce a longer high resistance path.

It has been found that a flow of one or two amperes is sufficient to bring about this difference in contact resistance at the negative and positive contacts.

Furthermore it makes no difference whether the brushes are trailing each other, which indicates that the deposited film is not the controlling factor.

L. R. Ludwig: In the paper the authors have attempted to describe a "film" on the brush surface which prevents intimate electrical contact between the brush and commutator except at discreet points. The description of this "film" was kept quite general, because at present its exact nature remains undetermined. Mr. Hellmund in his discussion has given further examples of what such a "film" may be like; for example he has supposed that it may consist of small carbon particles rolling between the brush and commutator. The properties which the "film" must have may be comparatively well defined, in that a diminution in the area of the film is to be expected with an increase in the temperature of the contact points, and that the phenomena must be reversible. Mr. Hellmund has explained this reversibility as due to motion of the commutator. This is a possible explanation, but not a necessary one. It is well known that an adsorbed gas film which has been driven off due to high temperature, will immediately re-form if the temperature is reduced.

Mr. Hellmund has mentioned the continuous motion of the points of contact between brush and commutator which probably takes place. It may be well to point out, however, that this continuous "shifting about" of the points of intimate contact is slower than the heating or cooling of the contact points. If this were not the case, variation in contact drop would be a function of the motion of the points only, and would not depend on temperature in the way shown by Fig. 2 of the paper.

The initial irregularity in brush contact when a commutator machine is first started has been pointed out by Mr. Heath. The authors have oscillograms of this phenomenon, and have explained it in section III of their paper as being due to the necessity of re-establishing of the "polishing" action.

Mr. Heath speaks of air films on the brush surface as faults which one may attempt to correct by slotting the brushes. With slip rings it is desirable to have the lowest possible contact drop at the brush surface and any insulating film may well be considered as a fault, but with commutators this film results in the contact drop which makes practical operation of commutating machinery possible. Without some form of film, it is doubtful if commutation could be satisfactorily accomplished at all. The films described in the paper of which an adsorbed (not absorbed) gas film is typical, are not to be gotten rid of by simply slotting the brushes. These films cling very tenaciously, and even in high vacuum, they are still to be found. The nature of the film and its behavior to variations in temperature depends on the gases present, and hence chemical fumes and moisture in the air may be expected to affect commutation as Mr. Heath has pointed out. Of course in practical operation extraneous films of oil for example, may be found on commutators which have an important effect on operation; but which play no part in the fundamental phenomena of the contact. Research done to establish the fundamental theory involved can only be begun with simple conditions in which cleanliness is essential.

The authors have used the term "polished surface" to devote one having a large number of regions at which electrical contact is possible. Although this would generally be expected to be the same as a mechanically polished surface, it seems possible that with some brush materials the "electrical polish" is better when the surface appears pin pinched as described by Mr. Heath. In the case he mentioned one would expect the number of contact areas to be less when running at light load than at full load, regardless of the surface appearance.

In answer to Mr. Stine, the authors used brushes having a specific resistivity independent of the direction of measurement.

The heat produced by friction was not neglected in the calculations which were made, but it plays no part in heating the contact points because most of the friction is not at these points, but is due to the presence of the "film" away from the points. This film has been found to withstand the pressure of brush on the commutator. (See paper by Schröter, *Archiv. für Elek.* 1927, p. 111 and 1931, July 15.)

The variation in brush resistivity with temperature was not taken into account in calculating the potential drop at the contact points, except that calculation showed this effect to be insufficient to explain the observed shape of the brush drop curves, in itself. The calculations given in the paper are therefore only approximate.

There seems to be no evidence for either electrical or thermal drop between a commutator and the contact point on a brush. A thermocouple placed at the brush surface (in so far as this is possible) would not measure the temperature of the contact points, because of the thermal as well as electrical drop in the material very near the contact points. This fact together with the fact that the friction is mainly away from the contact points proper readily explains why a brake shoe may have a temperature higher than the wheel upon which it is bearing. Actually, it is practically impossible to measure directly the temperature of the contact points themselves. It must be remembered too that mechanical contact persists at regions other than the region of electrical contact.

Mr. Stine has noted a non-symmetrical drop on alternating current by using a meter. This cannot be explained without more data, but the effect is not general as indicated by the symmetrical drop on alternating current shown in the oscillogram in Fig. 3 of the paper.

Single-Phase Short-Circuit Torque of a Synchronous Machine

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Synopsis.—This paper extends the analysis of synchronous machines previously published by Doherty and Nickle to include the calculation of torque due to single-phase short circuit. The torque is expressed as the sum of odd and even harmonic series which are simply related to those previously derived for the armature current. The effect of amortisseur windings is also taken into account.

As an illustration of the application of the equations, the short-circuit torque is calculated for a 100,000-kva. generator.

The mathematical analysis is given in Appendixes as follows:
A. Short-circuit armature current. B. Short-circuit torque. C. Decrement factors. D. Single-phase and three-phase reactances.

* * * * *

Introduction

THE analysis in this paper is based on those previously published by Messrs. R. E. Doherty and C. A. Nickle,[1,2,3,6] particularly on their paper *Synchronous Machines—IV*, which gives expressions for the currents resulting from single-phase short-circuit.

As the present paper is based on the theory and equations developed in *Synchronous Machines—IV*, the simplifying assumptions made therein are necessarily used here.

The most important of these assumptions are that:

1. Saturation is negligible.
2. The open-circuit voltage is sinusoidal.
3. Armature and field resistances are negligible except in determining decrements.
4. The short circuit occurs at no load.
5. Synchronous speed is maintained during short circuit.

Throughout the paper all quantities are expressed in the per-unit system unless otherwise noted, and instantaneous values of voltage, current, m.m.f., flux linkages, and torque are used.

General Procedure

The synchronous machine is considered as having a main field winding in the direct axis and amortisseur windings in both the direct and quadrature axes, thus introducing both subtransient and transient reactances.

The general procedure employed in *Synchronous Machines—IV*[3] is used to determine armature current and rotor excitation, except that three-phase line-to-neutral reactances are used in place of single-phase static reactances.

The values of the armature current and m.m.f. before the effect of the decrements is appreciable are determined by the open-circuit armature voltage e_o, the position of the rotor when short-circuit occurs, and the subtransient reactances. The armature m.m.f. is resolved into components over the direct and quadrature axes and is expressed in terms of odd and even harmonic series. The fundamental of the odd-series current induces a transient direct current in the direct-axis rotor circuits; all other harmonic components induce alternating currents in the rotor windings. Consequently, on short circuit the d-c. rotor excitation is increased from the value existing just before short circuit to a new value which includes a component induced in the two direct-axis rotor windings by the armature current. The decay of the induced d-c. components of excitation and that of the odd-series component of the armature current are determined by the decrement factors of the rotor windings in the direct axis.

It is assumed that the decay of the unsupported rotor excitation may be represented with sufficient accuracy by two decrement factors, one applying to the decay of induced direct currents in the amortisseur winding, and the other applying to the decay of that part of the d-c. component of field current which the exciter does not maintain. The "rotor linkage factor," F, represents the total rotor linkages, at any time after short circuit, as a fraction of the rotor linkage just before short circuit. Equation (**15a**) of Appendix A gives F as a function of time, in terms of machine constants.

The linkages in the short-circuited armature winding are maintained, at the instant just after short circuit, by the induced d-c. component of armature current. These linkages must decay with the d-c. component of armature current. For convenience, an "armature linkage factor," A, is introduced. It represents the linkages of the short-circuited armature winding at any time after short circuit, as a fraction of the maximum linkages of that winding before short circuit. Equation (**16a**) of Appendix A gives the expression for A. As shown by Doherty and Nickle,[3] the even-series components of armature current and the odd-series components of rotor excitation are proportional to the d-c. component in the armature, so that their decay is also represented by the armature linkage factor, A.

The detailed derivation of the expressions for short-circuit armature current is presented in Appendix A.

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1. For numbered references see Bibliography.

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32-72

In equation (**17a**) the current is expressed in finite trigonometric form, while equation (**18a**) gives the equivalent Fourier series expansion.

The short-circuit torque is expressed in terms of the components of armature current and rotor excitation in the direct and quadrature axes. In Appendix B expressions for torque are derived, first in finite trigonometric form (equation **6b**), and second, as the sum of odd and even harmonic series (equation (**9b**).

Summary of Results. The per-unit single-phase short-circuit torque is

$$T = \frac{2FAe_o^2}{x_2 + x_d''}\{\sin(t+\alpha) + 3\,b\sin 3(t+\alpha) + 5\,b^2\sin 5(t+\alpha) + \ldots\}$$

$$-\frac{e_o^2}{x_2 + x_d''}\left[F^2\frac{x_2}{x_2 + x_d''} + A^2\frac{x_2 - x_d''}{x_2}\right]\{2\sin 2(t+\alpha) + 4\,b\sin 4(t+\alpha) + 6\,b^2\sin 6(t+\alpha) + \ldots\}$$

where

e_o = per-unit armature voltage before short circuit

x_d'' = direct-axis subtransient reactance

x_q'' = quadrature-axis subtransient reactance

x_2 = $\sqrt{x_d'' x_q''}$ = negative-sequence reactance

α = angular position of the direct axis at the instant of short circuit, measured in the direction of rotation from the axis of the armature winding

and

$$b = \frac{x_2 - x_d''}{x_2 + x_d''} = \frac{\sqrt{x_q''} - \sqrt{x_d''}}{\sqrt{x_q''} + \sqrt{x_d''}}$$

F = rotor linkages as a fraction of their initial value (see equation (**15a**))

A = armature linkages as a fraction of their maximum value before short circuit, that is, as a fraction of their value on open circuit when the axis of the armature winding coincides with the direct axis of the rotor (see equation (**16a**))

From an inspection of the above equation it appears that the odd harmonic components of torque are due to the interaction of rotor and armature magnetic fields and that these components disappear as the trapped armature linkages die out. For the case of a short circuit with zero initial armature linkages no odd harmonic torques are present.

A part of the even harmonic torque is proportional to the square of the armature linkages and this part disappears when the subtransient reactances in the direct and quadrature axes are equal. This may be considered as a "reluctance torque" due to the variation in the permeance which the rotor offers to the trapped armature flux. Likewise the part of the torque which is proportional to the square of the rotor linkages is due to the variation in the permeance which the armature offers to the rotor flux.

It is interesting to note that, immediately after a short circuit with maximum armature linkages, the maximum value of second-harmonic torque due to the field linkages alone is $x_2/(x_2 + x_d'')$ times the maximum fundamental torque, while the maximum value of second-harmonic torque due to armature linkages alone is $(x_2 - x_d'')/x_2$ times the maximum fundamental torque. The maximum value of total second-harmonic torque just after a short circuit with maximum armature linkages is $(2\,x_q'' - x_d'')/(x_q'' + x_2)$ times the maximum value of fundamental torque. This ratio varies from 0.5 for $x_d'' = x_q''$ to 1.25 for $x_d'' = 0.2\,x_q''$. Thus the maximum values of fundamental and second-harmonic torque are of comparable magnitude just after short circuit.

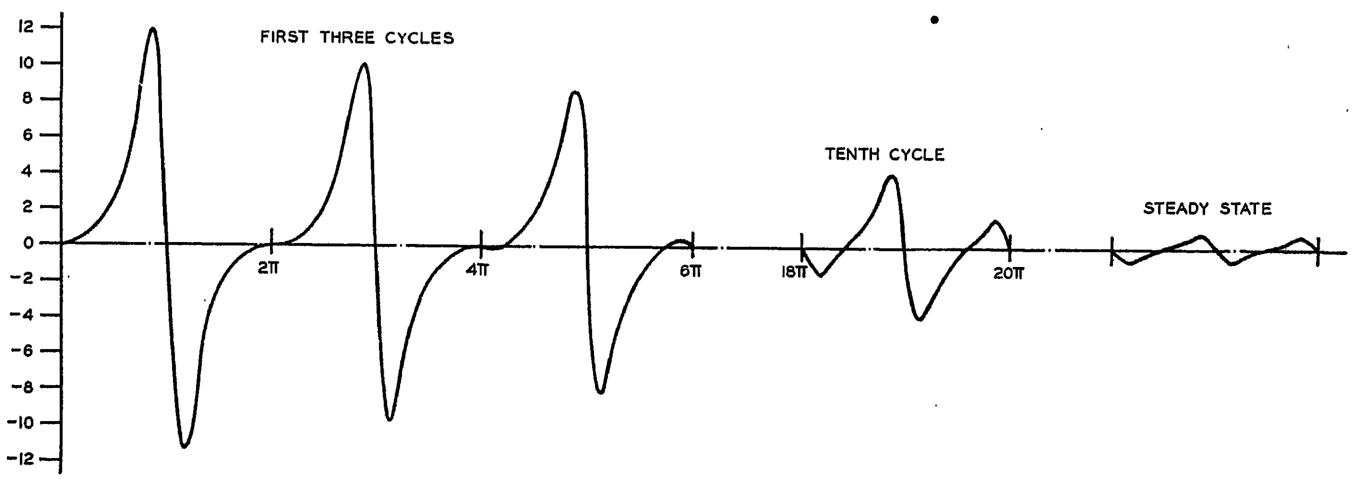

Fig. 1—Single-Phase Short-Circuit Torque of 100,000-Kva. Alternator, Maximum Initial Armature Linkages

$$\text{Torque} = -\frac{2F\,(F\cos t - A)\sin t}{H} - \frac{0.438\,(F\cos t - A)^2\sin 2t}{H^2}$$

$$= 5.25\,FA\,(\sin t + 0.669\sin 3t + 0.249\sin 5t + \ldots.)$$
$$-(3.21\,F^2 + 1.92\,A^2)(\sin 2t + 0.446\sin 4t + 0.149\sin 6t + \ldots)$$

$F = 0.449 + 0.417\,\epsilon^{-0.0021t} + 0.134\,\epsilon^{-0.069t}$; $A = \epsilon^{-0.025t}$; $H = 0.515 - 0.219\cos 2t$

Since the armature linkages eventually disappear, the steady-state torque is made up entirely of even harmonic components.

To illustrate the use of the formulas developed, numerical results have been calculated for a 60-cycle testing generator rated at 100,000 kva. The per-unit constants of the machine, as determined by test, are as follows:

$$x_d = 0.615; \quad x_d' = 0.207; \quad x_d'' = 0.148$$
$$x_q = 0.412; \quad x_q' = 0.412; \quad x_q'' = 0.367$$
$$\sigma_a = 0.025; \quad \sigma_f' = 0.0021; \quad \sigma_f'' = 0.069$$

Hence $x_2 = 0.233$; $b = 0.223$

Figs. 1 and 2 show the line-to-line short-circuit torque with maximum initial armature linkages and zero initial armature linkages respectively, as computed from the formulas derived.

From the standpoint of mechanical design of the machine and its foundations the condition which gives maximum torque is the most important. It is evident that for this purpose it is sufficient to consider the torque with maximum initial armature linkages. In the case of the machine considered, the peak value of torque under this condition is nearly 12 times full-load torque. It is to be noted that this high peak value is largely due to the presence of trapped armature linkages, since with no armature linkages the peak value of torque is only 4 times normal.

The trapped armature linkages are also responsible for all odd harmonic components of torque. Fig. 2 shows that with no trapped armature linkages the torque is made up entirely of even harmonics and in Fig. 1 it is seen that the odd harmonics decay gradually so that the torque curve approaches that of Fig. 2.

It appears from the equations in Appendix B that the short-circuit torque is the same for line-to-line and line-to-neutral short circuits. This is exactly true for an ideal machine and is true for actual machines to the extent that $x_o/2$ is negligible in comparison with x_d'' and x_q'' (see Appendix D). Although the armature *currents* resulting from the two types of short circuit of an ideal machine are different, the armature *m.m.fs.* are the same.

The consideration of machine losses would somewhat modify the torque as calculated in this paper. The correction for losses can be calculated approximately in a given case, but this correction is generally small enough to be neglected.

ACKNOWLEDGMENT

The authors gratefully acknowledge the many valuable suggestions of Mr. Alan Howard, regarding both the theory and its presentation, and the helpful criticisms of Mr. P. L. Alger and Mr. R. H. Park. They also wish to acknowledge the assistance of Mr. R. W. Smith in checking the equations, and of Mr. N. V. Cargill in calculating and plotting the curves.

Appendix A

SHORT-CIRCUIT ARMATURE CURRENT

Doherty and Nickle have shown[3] that the armature current resulting from single-phase short circuit is

$$i = \frac{2\,k e_o\,[\cos(t+\alpha) - \cos\alpha]}{(x_D'' + x_Q'') + (x_D'' - x_Q'')\cos 2\,(t+\alpha)} \tag{1a}$$

where

$k = 1$ for line-to-neutral short circuit

$k = \sqrt{3}$ for line-to-line short circuit

e_o = armature voltage before short circuit

α = angular position of the direct axis at the instant of short circuit, measured in the direction of rotation from the axis of the armature winding

and x_D'' and x_Q'' are respectively the direct- and quadrature-axis single-phase static reactances of the short-circuited armature winding.

Changing to three-phase reactances, as in equation (1d) of Appendix D, the current is

$$i = \frac{3\,e_o\,[\cos(t+\alpha) - \cos\alpha]}{kH} \tag{2a}$$

where

$$H = (x_d'' + x_q'') + (x_d'' - x_q'')\cos 2\,(t+\alpha) \tag{3a}$$

As shown in reference 3, equation (2a) may be resolved into harmonic components as follows:

$$i = \frac{3\,e_o}{k\,(x_d'' + x_2)}\,\mathbf{O} - \frac{3\,e_o\cos\alpha}{2\,kx_2}\,\mathbf{E} \tag{4a}$$

where $x_2 = \sqrt{x_d''\,x_q''}$ is the negative sequence reactance

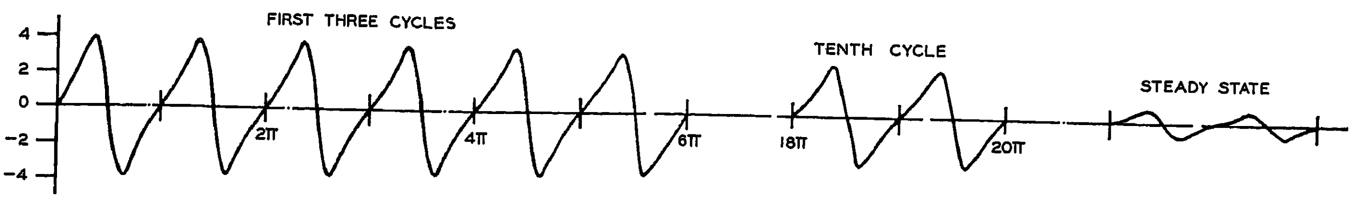

FIG. 2—SINGLE-PHASE SHORT-CIRCUIT TORQUE OF 100,000-KVA. ALTERNATOR, ZERO INITIAL ARMATURE LINKAGES

$$\text{Torque} = \frac{0.734\,F^2 \sin 2\,t}{H^2}$$
$$= 3.21\,F^2\,(\sin 2\,t - 0.446 \sin 4\,t + 0.149 \sin 6\,t - \ldots)$$
$$F = 0.449 + 0.417\,\epsilon^{-0.0021\,t} + 0.134\,\epsilon^{-0.069\,t}; \quad H = 0.515 + 0.219 \cos 2\,t$$

of the machine applicable to the condition of dead short circuit, and where

$$\mathbf{O} = \text{odd series} = \frac{(x_d'' + x_2)\cos(t+\alpha)}{H}$$

$$= \cos(t+\alpha) + b\cos 3(t+\alpha) + b^2 \cos 5(t+\alpha) + \ldots$$

$$= \sum_{n=1,3,\ldots} b^{\frac{n-1}{2}} \cos n(t+\alpha) \tag{5a}$$

$$\mathbf{E} = \text{even series} = \frac{2x_2}{H}$$

$$= 1 + 2b\cos 2(t+\alpha) + 2b^2 \cos 4(t+\alpha) + \ldots$$

$$= 1 + \sum_{n=2,4,\ldots} 2b^{\frac{n}{2}} \cos n(t+\alpha) \tag{6a}$$

and

$$b = \frac{\sqrt{x_q''} - \sqrt{x_d''}}{\sqrt{x_q''} + \sqrt{x_d''}} = \frac{x_2 - x_d''}{x_2 + x_d''} \tag{7a}$$

The direct-axis component of the armature current is

$$i_d = \frac{2k}{3} i \cos(t+\alpha)$$

$$= \frac{2e_o}{x_d'' + x_2}\mathbf{O}\cos(t+\alpha) - \frac{e_o \cos\alpha}{x_2}\mathbf{E}\cos(t+\alpha) \tag{8a}$$

Only the average value of this current can induce transient d-c. excitation in the direct-axis rotor circuits. All other components induce alternating excitation. The average value of the even-series components of current is zero, and the average value of the odd-series components is

$$\frac{e_o}{x_d'' + x_2} \tag{9a}$$

The sudden appearance of this direct-axis armature current induces the initial d-c. rotor excitation

$$\Delta'' I_{de}\text{ (d.c.)} = \frac{(x_d - x_d'')e_o}{x_d'' + x_2} \tag{10a}$$

as shown in *Synchronous Machines—III.*[2] Thus the total d-c. excitation due to currents in the direct-axis rotor windings at the instant immediately after short circuit is

$$e_o + \Delta'' I_{de}\text{ (d.c.)} = e_o \frac{x_d + x_2}{x_d'' + x_2} \tag{11a}$$

The exciter voltage maintains only a part of this excitation, and the decay of the unsupported part is determined by the decrement factors of the rotor circuits.

Now if the decrement of the main field is very much smaller than that of the amortisseur winding, as is generally the case, the decay of the linkages supported by each of the circuits can be considered separately. Assuming the decay of induced direct current in the amortisseur to be practically completed before the decay of main field linkages is appreciable, the average value of the direct-axis component of armature current due to the linkages supported by the field winding alone is

$$\frac{e_o}{x_d' + x_2} \tag{12a}$$

The d-c. excitation due to the main field current alone is, therefore,

$$e_o + \Delta' I_{de}\text{ (d.c.)} = e_o \frac{x_d + x_2}{x_d' + x_2} \tag{13a}$$

The difference between this excitation and the excitation e_o, which is supported by the exciter, decays according to the field decrement, σ_f'. Likewise the difference between the excitations expressed by (**11a**) and (**13a**) decays according to the direct-axis amortisseur winding decrement, σ_f''. Thus the total d-c. excitation in the direct axis at any time after short circuit may be written as

$$I_{de}\text{ (d.c.)} = \frac{x_d + x_2}{x_d'' + x_2} F e_o \tag{14a}$$

where F is a factor representing the decay of the direct-axis linkages. F has the value

$$F = \frac{x_d'' + x_2}{x_d + x_2} + \frac{(x_d'' + x_2)(x_d - x_d')}{(x_d + x_2)(x_d' + x_2)}\epsilon^{-\sigma_f' t} + \frac{x_d' - x_d''}{x_d' + x_2}\epsilon^{-\sigma_f'' t} \tag{15a}$$

F is unity at the instant just after short circuit.

Since the odd-series components of armature current are due to rotor linkages the magnitudes of these components at any time after short circuit are F times their initial magnitudes.

The even-series components of armature current are due to the trapped armature linkages. Since these linkages are unsupported they decay in accordance with the armature decrement, σ_a, and the even-series components of armature current decay at the same rate. For convenience, the quantity

$$A = \epsilon^{-\sigma_a t}\cos\alpha \tag{16a}$$

is chosen to represent the trapped armature linkages at any time after short circuit occurs, as a fraction of the maximum armature linkages before short circuit.

Inserting the armature and field linkage factors, A and F respectively, in equations (**2a**) and (**4a**), the armature current at any time after short circuit is

$$i = \left(\frac{3}{2k}\right)\frac{2e_o[F\cos(t+\alpha) - A]}{H} \tag{17a}$$

or

$$i = \frac{3}{2k}\left[\frac{2e_o F}{x_d'' + x_2}\mathbf{O} - \frac{e_o A}{x_2}\mathbf{E}\right] \tag{18a}$$

where **O** and **E** are the series previously defined.

Appendix B

Short-Circuit Torque

The general expression for the torque of a synchronous machine is given by R. H. Park.[5] Equations (**11**), (**12**) and (**19**) of reference 5 may be combined to give the torque in terms of the direct and quadrature-axis components of armature current and equivalent rotor excitation. The result is

$$T = i_q I_{de} - i_d I_{qe} - i_d i_q (x_d - x_q) \tag{1b}$$

where i_d and i_q are the direct and quadrature-axis components of armature current, and I_{de} and I_{qe} are the equivalent rotor excitations in direct and quadrature axes respectively, including the excitation due to induced currents in field and amortisseur windings.

The armature current, i, is given by equation (**17a**). Its components in the direct and quadrature axes are

$$i_d = \frac{2k}{3} i \cos(t + \alpha)$$

$$= \frac{2e_o[F\cos(t+\alpha) - A]\cos(t+\alpha)}{H} \tag{2b}$$

and

$$i_q = -\frac{2e_o[F\cos(t+\alpha) - A]\sin(t+\alpha)}{H} \tag{3b}$$

where F, A and H are defined by equations (**15a**), (**16a**) and (**3a**) respectively.

The total equivalent rotor excitation in the direct axis is the sum of the initial excitation, multiplied by the field decay factor F, and the excitation induced due to the armature current. The total equivalent direct-axis rotor excitation is, therefore,

$$I_{de} = e_o F + i_d (x_d - x_d'')$$

$$= e_o F + \frac{2e_o(x_d - x_d'')[F\cos(t+\alpha) - A]\cos(t+\alpha)}{H} \tag{4b}$$

Since there is no initial quadrature-axis excitation the equivalent excitation in the quadrature axis is

$$I_{qe} = i_q (x_q - x_q'')$$

$$= -\frac{2e_o(x_q - x_q'')[F\cos(t+\alpha) - A]\sin(t+\alpha)}{H} \tag{5b}$$

Substituting these expressions in (**1b**) the torque is

$$T = -\frac{2e_o^2F[F\cos(t+\alpha) - A]\sin(t+\alpha)}{H}$$

$$+\frac{2e_o^2(x_d'' - x_q'')[F\cos(t+\alpha) - A]^2\sin 2(t+\alpha)}{H^2} \tag{6b}$$

For the case of zero initial armature linkages, $\alpha = \pi/2$ and the above expression reduces to

$$T = \frac{2e_o^2 x_q'' F^2 \sin 2t}{H^2} \tag{7b}$$

Equation (**6b**) is suitable for the calculation of the instantaneous torque at any time after short circuit. However it is also desirable to express the torque in terms of harmonic components. This may be done by substituting in (**6b**) the odd and even series, as defined by (**5a**) and (**6a**), for their equivalent trigonometric expressions. The result is

$$T = -\frac{e_o^2F}{x_2}[(1+b)FO - AE]\sin(t+\alpha)$$

$$+\frac{e_o^2(x_d'' - x_q'')}{2x_2^2}[(1+b)FO - AE]^2\sin 2(t+\alpha) \tag{8b}$$

since $\quad 1 + b = \dfrac{2x_2}{x_2 + x_d''}$ (see equation (**7a**))

This expression involves the squares and products of even and odd series. Expanding equation (**8b**) and collecting coefficients of each harmonic, the torque is

$$T = \frac{e_o^2}{x_2 + x_d''}\left\{2FA\sum_{n=1,3,..} nb^{\frac{n-1}{2}}\sin n(t+\alpha)\right.$$

$$\left.-\left[F^2\frac{x_2}{x_2 + x_d''} + A^2\frac{x_2 - x_d''}{x_2}\right]\sum_{n=2,4,..} nb^{\frac{n-2}{2}}\sin n(t+\alpha)\right\} \tag{9b}$$

Appendix C

Decrement Factors

Doherty and Nickle have shown[3] that the decrement for the unsupported linkages in the main field, with the armature short-circuited single-phase, is

$$\sigma_f' = \frac{x_d + x_2}{x_d' + x_2}\sigma_o' \tag{1c}$$

where σ_o' is the decrement for unsupported field linkages with the armature open-circuited.

The decrement for the induced direct current in the amortisseur winding is determined by the resistance and apparent inductance of the amortisseur. The apparent inductance is determined by the amortisseur linkages which depend on the presence of the amortisseur current. It may be shown that under single-phase short-circuit conditions this apparent inductance is proportional to

$$(x_d'' + x_2)/(x_d' + x_2),$$

while for three-phase short circuit it is proportional to x_d''/x_d'. Since the decrements for the two cases are inversely proportional to the respective inductances the decrement for induced direct currents in the amortisseur on single-phase short circuit is

$$\sigma_f'' = \frac{x_d''(x_d' + x_2)}{x_d'(x_d'' + x_2)}\sigma_s'' \tag{2c}$$

where σ_s'' is the amortisseur winding decrement for three-phase short-circuit at the machine terminals.

As shown in reference 3 (Appendix H) the apparent per-unit inductance of the armature winding just after short circuit is

$$\sqrt{x_D'' x_Q''} = \frac{2\,k^2}{3}\,x_2 \tag{3c}$$

The per-unit resistance of the short-circuited winding is

$$\frac{k^2+1}{2}\,r \tag{4c}$$

Therefore the decrement for the d-c. component of armature current is

$$\sigma_a = \frac{3\,(k^2+1)}{4\,k^2}\;\frac{r}{x_2} \tag{5c}$$

where r is the per-unit armature resistance, line to neutral.

Since, in the per-unit system, time is measured, not in seconds, but in electrical radians traversed at the normal frequency f, the decrements above are $1/(2\pi f)$ times the reciprocals of the respective time constants in seconds.

It will be noted that the influence of the resistance of one winding on the decrement of other windings has been neglected. Doherty and Nickle[3] have discussed and justified this approximation so far as the effect of armature resistance on field decrement is concerned, and *vice versa*. The neglect of mutual effects in determining decrements of the direct-axis rotor circuits is justifiable to the extent that the decrements of the two circuits, considered separately, differ considerably in order of magnitude.

Strictly speaking, the amortisseur winding of a commercial machine generally consists of a number of circuits. However their decrements are usually of the same order of magnitude, so that sufficient accuracy is obtained by considering the amortisseur winding as having a single decrement.

Appendix D

Single-Phase and Three-Phase Reactances

Park and Robertson[4] have derived the relations between single-phase static reactances and the normal three-phase reactances of a synchronous machine. For example the direct axis single-phase subtransient reactance may be written

$$x_D'' = \frac{2\,k^2}{3}\,x_d'' \tag{1d}$$

for a line-to-line winding with $k = \sqrt{3}$

and
$$x_D'' = \frac{2\,k^2}{3}\left(x_d'' + \frac{x_o}{2}\right) \tag{2d}$$

for a line-to-neutral winding with $k = 1$. x_o is the zero-sequence impedance of the machine. Similar relations hold for the other reactances.

If $x_o/2$ is negligible compared with x_d'' equation (**2d**) evidently reduces to (**1d**). As this is nearly true for many machines, and as it simplifies the expressions, equation (**1d**) was used in changing from single-phase to three-phase reactances in Appendix A. If $x_o/2$ is not negligible, however, correct expressions for current and torque during line-to-neutral short circuit can be obtained by replacing, x_d'' by $x_d''+x_o/2$, x_d by $x_d+x_o/2$, etc. In this case x_2 must be replaced by

$$\sqrt{\left(x_d'' + \frac{x_o}{2}\right)\left(x_q'' + \frac{x_o}{2}\right)}$$

which is approximately $x_2 + x_o/2$. For line-to-line short circuit the expressions for current and torque are correct as given.

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5. *Two-Reaction Theory of Synchronous Machines*, Park, A.I.E.E. Trans., Vol. 48, No. 3, 1929, p. 716.

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Discussion

L. A. Kilgore: In this paper the authors have presented a relatively simple solution to the difficult problem of calculating the pulsating torque on single-phase short circuits. They have applied the extended two-reaction theory and the constant interlinkage theorem in order to include the affect of direct and quadrature axis damping circuits.

The form of the solution obtained shows up quite well the components of the torque. The main part of the double frequency component is due to the field flux and the single-phase alternating current in the stator. The fundamental frequency torque is due to the flux trapped in the armature circuit reacting on the current in the field. The other harmonics given by the series used in the paper are due only to the difference in the reactance on the two axes. For a machine with a damper winding, the differences are generally small and the harmonics are negligible, except where there is a possibility of mechanical resonance.

The assumptions made in obtaining this solution are sufficiently accurate in most cases, but it is worth while considering the limitations. The authors neglect armature and field resistance, except in determining decrement. This gives accurate results for the pulsating torque, except for a synchronous motor with a high resistance damper winding where the calculated value will be too high, since current is limited appreciably by resistance as well as reactance.

The average torque produced by the resistance losses may be small in comparison with the maximum values of pulsating torque, but it is not always negligible. In cases where there is appreciable external resistance or a high negative sequence resistance, the average torque may be several times the rated value.

Such a torque when suddenly applied can not be neglected in the practical problem of designing spring mountings of single-phase machines.

The authors assume that the difference between the direct and quadrature axis single-phase reactance varies as a second harmonic function of the rotor position. The actual variation with position may contain other harmonics, especially in the case of machines without dampers. These variations may introduce high harmonics of the same order of magnitude as those calculated by the formulas. However, this will not greatly affect the maximum value of the torque.

An earlier paper by G. W. Penney* dealt with the special case of machines without damper windings. Mr. Penney calculated the short-circuit torque from the change in stored magnetic energy. The authors of this paper use the equation (**1b**):

$$T = i_q I_{de} - i_d I_{qe} = i_d i_q \,(X_d - X_q),$$

and refer to a paper by R. H. Park (reference number 5) for the proof. In deriving this expression Mr. Park started with the fundamental relation (total power output) = (mechanical power input) + (rate of decrease in stored magnetic energy) − (total ohmic losses). In order to eliminate the consideration of stored magnetic energy, he calculated the power output assuming that all the stator and rotor currents remain fixed for the moment. Perhaps the authors can give a more direct physical explanation of this equation.

B. L. Robertson: In 1923 R. E. Doherty pointed out† that the short-circuit torque of a synchronous machine could be obtained from the time rate of change of the stored magnetic energy in the machine. Making use of the assumptions which Doherty had stated, and also employing relations previously given in discussions on mechanical forces between electric circuits, Penney presented in 1926 "Short-Circuit Torque in Synchronous Machines." The paper quite well analyzed in a qualitative manner the production of short-circuit torque for what he called an "ideal machine." The results showed that the torque was alternating in character, never pulsating; that it rose to very high values at regular intervals; and that single-phase short-circuits gave rise to torques greater than three-phase short-circuits.

As specifically pointed out by Penney, and as shown in his and the present paper, the torque of a short-circuited machine is not zero which is often thought to be the case. The average may be small (it is exactly zero if all losses are zero), but the actual torque periodically increases to very high values, and as has just been shown the peaks may be 12 times normal for the worst case of short circuit. Design, which must be based on these worst cases, must account for such peaks, part of this torque being transmitted to the shaft and to the stator supports.

It is perhaps of value to note the assumptions made in the earlier work on this subject. There were no resistance, round rotor, and no secondary windings on the field structure. In contrast, the present paper treats with the general salient pole machine, having an amortisseur winding in both direct and quadrature axes. Resistance in the circuit impedances of the machine is neglected as before, but it is taken into account in the decrement factors. Furthermore, the solution gives the complete transient short-circuit torque curve and hence does far more than merely get the end points, initial and steady-state. To realize the exactness of solutions when resistance is so included one is referred to a paper† by Doherty and Nickle which contains what is perhaps the most outstanding agreement between test and calculated results for complicated circuit problems.

It is interesting to note that whereas the armature current waves are decidedly different in form for the two transient cases of short-circuit at maximum and minimum flux linkages, the wave shapes for all torques bear a similarity to each other for each oscillation about the axis. It is realized, of course, that for short circuit at minimum linkages the torque curve for the first several cycles is of twice the frequency of that for short circuit at maximum linkages, and that over a certain period of the transient the similarity is somewhat lost. Although previous wave shapes are in general appearance like the present ones developed, the latter are more exact because of generalities and broader assumptions underlying their derivation.

In concluding this discussion I would like to point out the continued use of the theorem of constant linkages. This theorem was first given by Doherty in 1918, quite fully discussed by him in 1923, and soon thereafter applied by Laffoon, Franklin, and Karapetoff to synchronous machines, but only of the round rotor type. Doherty,‡ however, applied this theorem to the salient pole machine and in consequence it underlies this latest work on short-circuit torques. It is of considerable interest to see the remarkable results which this simple theorem has given through its use, and it is another example of the practical application of fundamental laws formulated in physics so long ago.

Alan Howard: It is well known that the short-circuit time-constant of the main field of a synchronous machine has a definite relation to the type of short circuit, this relation having been determined by several authors. The time-constant of the amortisseur winding of a synchronous machine is affected by the type of short circuit in a somewhat similar manner but the relations, such as given in equation (**2c**) of the paper, are less well known, and it may, therefore be of interest to derive them.

The amortisseur time-constant is the ratio of the apparent inductance of the amortisseur to its resistance. The short circuit does not affect the resistance, so the problem is to determine its effect upon the inductance. This will be done first for the case of a symmetrical three-phase short-circuit through a reactance x, under the same assumptions as are used in the paper. The time-constant under single-phase conditions is easily derived from this result.

The amortisseur linkages at any time may be represented as

$$\psi_k = a i_k + b i_f + c i_d$$

where a, b and c are constants, i_k and i_f are the amortisseur and field currents respectively, and i_d is the direct axis component of armature current.

The amortisseur linkages immediately after short circuit, before the amortisseur currents have decreased appreciably are equal to the linkages before short circuit which are,

$$\psi_{ko} = b i_{fo} = b e_o$$

After the amortisseur current has disappeared, but before the field linkages have changed appreciably, the direct axis armature and field currents will be

$$i_f = i_{fo} \frac{x_d + x}{x_d' + x} = e_o \frac{x_d + x}{x_d' + x}$$

$$i_d = \frac{e_o}{x_d' + x}$$

Thus the amortisseur linkages become

$$\psi_{k1} = \frac{e_o}{x_d' + x} \,[b\,(x_d + x) + c]$$

The change in linkages due to the disappearance of the amortisseur current is, then

$$\Delta\psi_k = \psi_{ko} - \psi_{k1} = \frac{-\,e_o}{x_d' + x} \,[c + b\,(x_d - x_d')]$$

The initial value of i_d is

$$i_{do} = \frac{e_o}{x_d'' + x}$$

**Short-Circuit Torque in Synchronous Machines without Damper Windings* A.I.E.E. Trans. 1929, Vol. 48, p. 1230.

†*A Simplified Method of Analyzing Short-Circuit Problems,* A.I.EE. Trans. 1923, p. 841.

‡*Synchronous Machines—IV,* A.I.E.E. Trans. 1928, p. 457.

and since the circuits are linear, the initial amortisseur current is proportional to i_{do} or

$$i_{ko} = d \frac{e_o}{x_d'' + x}$$

where d is a constant.

The apparent amortisseur inductance is thus,

$$L_k = \frac{\Delta\psi_k}{i_{ko}} = \frac{x_d'' + x}{x_d' + x}\left[\frac{c + b(x_d - x_d')}{d}\right]$$

where the constants b, c, and d are undetermined.

The time-constant varies directly as the inductance with changes in external reactance since the amortisseur resistance is constant. Thus the ratio of the time-constant for a three-phase short circuit through an external reactance x to that for a terminal short circuit is

$$\frac{T_k}{T_{ks}} = \frac{L_k}{L_{ks}}$$

where T_k is the amortisseur time-constant and subscript s denotes quantities applying to a terminal short circuit.

The time-constant T_{ks} is usually referred to as *the* amortisseur time-constant and is usually the one for which the numerical value is most readily available. It is therefore convenient to express the time-constant applying to other short-circuit conditions in terms of T_{ks}. T_k thus becomes

$$T_k = \frac{x_d'(x_d'' + x)}{x_d''(x_d' + x)} T_{ks}$$

In terms of decrements, using the notation of the paper

$$\sigma'' = \frac{x_d''(x_d' + x)}{x_d'(x_d'' + x)} \sigma_s'' = \frac{1}{T_k}$$

The time-constants and the average values of the direct axis currents in an unsymmetrical short circuit are the same as those occurring in a symmetrical three-phase short circuit through a definite value of series reactance. This series reactance is x_2 for a single-phase line-to-line short circuit, so that the amortisseur decrement in this case becomes

$$\sigma_f'' = \frac{x_d''(x_d' + x_2)}{x_d'(x_d'' + x_2)} \sigma_s''$$

which is equation (2c) of the paper. For a line-to-neutral short circuit the decrement would be,

$$\sigma'' = \frac{x_d''(x_d' + x_2 + x_o)}{x_d'(x_d'' + x_2 + x_o)} \sigma_s''$$

Wire Communication Aids to Air Transportation

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Member, A.I.E.E.

RAPID development of air transportation in this country has continued through the past few years and today established routes connect nearly all important cities. The route mileage of the airways in the United States as shown in Fig. 1 totals over 30,000 miles. Regularly scheduled transport service is given on practically all of these routes and considerable use of them is also made by military and private planes. Figures relating to service of air transport companies seem particularly significant. The Department of Commerce reported approximately 42,800,000 miles flown in passenger, mail, and express service on domestic scheduled lines in 1931, an increase of 35 per cent over the preceding year and more than a fourfold increase since 1928. In the same three-year period passengers carried increased ninefold, reaching a total of around 470,000 in 1931. Along with this growth safety has been increased as indicated by the respective 1928 and 1931 reports of 250,000 and 750,000 miles flown per accident. Reasonable regularity of schedules on air transport lines also has been maintained, the ratio of miles actually flown to scheduled miles last year being in the order of 92 per cent. Communication facilities have been an important contributing factor to all this development and improvement.

It was early recognized that fast and reliable communication would be needed in connection with any extensive development of air transportation. Communication with planes in flight was an obvious requirement and this could be provided only by radio. For land service, however, experience has indicated that wire facilities best meet the general requirements. This paper describes the wire communication facilities in general use today, both by the Government and by transport companies, as aids to air transportation.

Principal airways have been established largely through Federal aid. In addition to marking and lighting airways the Airways Division of the Department of Commerce had provided up to April 1, 1932, 67 radio telephone stations at approximately 200-mile intervals as indicated in Fig. 1, to be used for broadcasting weather reports and similar information to planes in flight and for transmitting directive radio beacon signals for enabling planes to keep on the course. In conjunction with these services it had contracted for 24-hour teletypewriter service along 13,000 miles of main airways connecting some 250 stations, principally for the purpose of transmitting weather reports and to assist in dispatching the planes. All of these facilities have been made available without cost to aircraft operating companies and others using the airways. In addition to this communication service contracted for by the Government, approximately 5,000 miles of teletypewriter circuit are used daily in furnishing private wire communication service to a number of transport companies for transmitting information pertaining to the operation of their own lines. Routes on which these facilities are furnished are indicated by heavy lines in Fig. 1.

When the first air mail service was established, radio telegraph was introduced as a means of point-to-point communication along the New York-Chicago-San Francisco airway route. At each radio station meteorological data were collected from surrounding points by means of long distance telephone and telegraph and these data were exchanged periodically through the day with the other stations over the radio telegraph.

With a rapid expansion foreseen in air transport service it was apparent there would be a large increase in communication requirements not only to equip new routes but to handle increased volume on existing routes. There was the definite requirement for radio telephone communication with planes which would need a number of the radio channels allotted to this service. Considering these factors and the geographic and other conditions applying to probable development of air transportation in the United States, it seemed that regular point-to-point service served by radio telegraph could be provided more satisfactorily in another way.

Arrangements were made in 1928 for teletypewriter communication services at several points connecting radio stations with their local weather bureau offices in order to expedite the delivery of weather reports and other traffic handled by radio telegraph. Shortly afterward, a teletypewriter system was installed on the New York-Cleveland route connecting the Department of Commerce and Weather Bureau stations at Hadley Field, Stelton, N. J., and Cleveland, Ohio, and a number of intermediate points. This type of service seemed ideally fitted for use in weather reporting and plane dispatching and has been extended to replace the service furnished by the radio telegraph system and to provide for communication requirements on other routes. It offers the advantages of simultaneous communication with any number of stations desired, the communications being automatically recorded on machines at each point. A message using code or abbreviations, if desired, can be sent instantly without the necessity of calling in or checking with the receiving stations and the immediate attention of only the sending operator is required. Automatic recording reduces the possibility of human error and permits the most efficient use of operating personnel with resulting savings in labor. Furthermore, as contrasted with radio, this system, utilizing wire

*Long Lines Dept., American Telephone and Telegraph Co., New York.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

transmission, is not so subject to variations in meteorological conditions, is more dependable, and has the advantage of being readily extended to handle large volumes of business. It is also well adapted for carrying on administrative and other work as well as for weather reporting and plane dispatching.

Transmission of Weather Reports

Material progress has been made in reducing the effect of weather hazards to air transportation, through the service rendered by the Department of Commerce and U.S. Weather Bureau in the collection and dissemination of weather reports supplemented by other own areas and make area forecasts every three hours based on data collected over the Department of Commerce circuits from connected airway stations and over commercial telegraph lines from other reporting points. These summaries and forecasts are then transmitted over the teletypewriter circuits and made available to all airway stations. While the forecasts include predictions as to storm developments or movements, conditions in specific localities are often likely to change rapidly and it has been necessary to provide additional reports along the air routes on an hourly basis in order to keep pilots continuously advised of conditions likely to be encountered. Consequently, the airway keepers

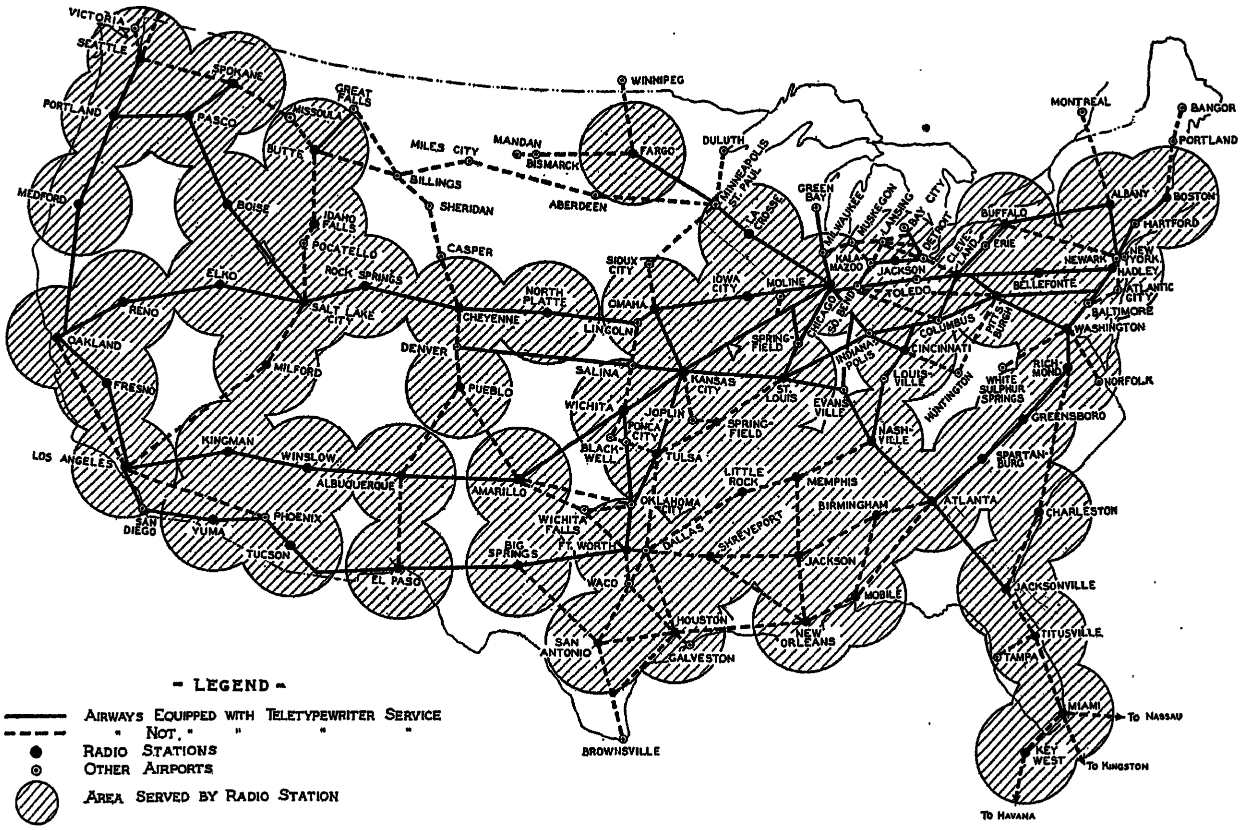

Fig. 1—Airway Map of the United States Showing Routes Equipped with Teletypewriter Service

reports collected by individual transport companies from planes in flight. For this service a system of practically continuous reporting and forecasting for areas along air routes has been developed and weather observations have been extended to include data of particular benefit to air navigation.

The teletypewriter networks furnished the Department of Commerce are devoted largely to this purpose and in conjunction with its radio telephone broadcasting service are the means for providing to pilots information relating to existing conditions and forecasts for both general and local areas.

Twelve selected Weather Bureau airport stations located at strategic points in the country's airway network prepare summaries of weather conditions in their and Weather Bureau observers at the various teletypewriter stations make local observations every hour of general weather conditions, ceiling height, visibility, wind direction and velocity, temperature, and barometric pressure. These data are then sent by teletypewriter and automatically recorded at all points on the circuit in accordance with a predetermined schedule, which is coordinated with the broadcast schedule of radio stations. Since pilots will tune in on particular stations at definite times to obtain reports in accordance with the broadcast schedule, it is important that the schedules be closely adhered to. The following is an illustration of scheduled weather reporting along the Newark-Cleveland route.

At 42 minutes past the hour the observers will begin

typing their observations on the circuit beginning with the Newark station, followed successively by Hadley, Allentown, Park Place, Numidia, Sunbury, Winkleblech, Bellefonte, Kylertown, Greenwood Club, Brookville, Mercer, Parkman and Cleveland, with practically no interval between the completion of the report from one station and the beginning of a report from the next. When the Cleveland weather observer has completed typing his report a complete record of weather conditions at all points on the circuit will appear on the teletypewriter tape at each individual station and in the radio broadcasting stations located at Hadley, Bellefonte, and Cleveland. Fig. 2 shows a portion of an actual tape record of an hourly report along the Newark-Cleveland route which includes the stations between Newark and Bellefonte, Pa. For convenience the tape has been cut to show one station report on each line. First the starting time, 0642 E.S., which is 6:42 a.m., Eastern Standard Time, is shown. Each reporting station in sequence then gives its code letter or letters and follows with a report of its observations. An interpretation of the report from the first station is "Newark, overcast, lower broken clouds, occasional sprinkling, estimated ceiling height 600 feet, visibility 2½ miles, wind velocity 8 miles per hour, direction northeast, temperature 42 deg., dew point 40 deg., barometric pressure 30.10 in." The time of actual transmission for all 14 stations, Newark to Cleveland, is generally about four minutes.

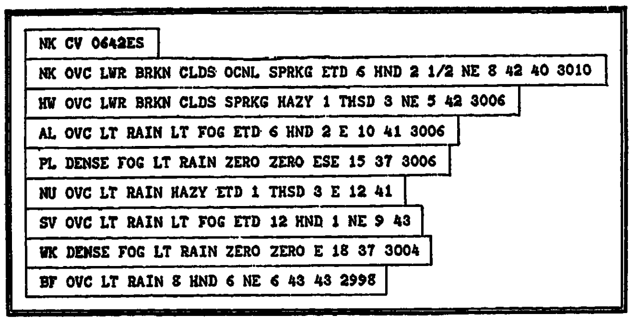
NK CV 0642ES
NK OVC LWR BRKN CLDS OCNL SPRKG ETD 6 HND 2 1/2 NE 8 42 40 3010
HW OVC LWR BRKN CLDS SPRKG HAZY 1 THSD 3 NE 5 42 3006
AL OVC LT RAIN LT FOG ETD 6 HND 2 E 10 41 3006
PL DENSE FOG LT RAIN ZERO ZERO ESE 15 37 3006
NU OVC LT RAIN HAZY ETD 1 THSD 3 E 12 41
SV OVC LT RAIN LT FOG ETD 12 HND 1 NE 9 43
WK DENSE FOG LT RAIN ZERO ZERO E 18 37 3004
BF OVC LT RAIN 8 HND 6 NE 6 43 43 2998

FIG. 2—TELETYPEWRITER TAPE WITH PORTION OF WEATHER SEQUENCE REPORT

At 50 minutes past the hour the three radio stations will interrupt the beacon signals and broadcast the reports just received. Hadley Station transmits the weather sequence received from stations between Newark and Bellefonte; simultaneously, the Bellefonte radio station transmits the entire sequence received from all points between Newark and Cleveland, and the Cleveland radio station broadcasts reports from points between Bellefonte and Cleveland. All three radio stations include in the sequence, reports of weather at Cleveland and New York. The range beacons are not interrupted for these reports for longer than two minutes, and if the reports require a longer period the beacon signals are restored for one minute and again interrupted to complete the reports.

Based upon the information obtained through the sequence collections, airway weather reporting stations retransmit, generally by teletypewriter, hourly weather reports to the various airway operating companies' offices in that vicinity. Airway companies maintain various arrangements for posting the weather information for the convenience to pilots. Some companies post the information on a series of boards of different color arranged in geographic sequence to represent different airway routes, each board indicating a particular point on that route.

An experimental service involving the transmission of weather summaries in map form has been tried out recently at Kansas City, Chicago, Cleveland, Newark, and Washington. A separate teletypewriter circuit equipped with page teletypewriters at each of these points was provided for this purpose. The weather maps were prepared at Kansas City and Cleveland every three hours and then transmitted over this circuit. A typical map transmitted from Kansas City is shown in Fig. 3, and the following describes briefly the methods used.

Two special airways maps, ordinary letter width, have been printed, one map covering the section of the country east of the Mississippi River and another the section west to the Rocky Mountains. The maps are printed in ink which permits hectograph reproduction. The airways, principal airports, and cities are shown on the map and in the upper left corner is a small circle used as a coordinating point.

At a scheduled time the operator at Kansas City or Cleveland inserts in a teletypewriter equipped for perforating tape a copy of the map on which the latest weather information has already been typed including general state of weather, ceiling height, visibility, temperature, wind direction and velocity, and barometric pressure for each point and isobars connecting points of equal pressure. The sending operator then types the identical symbols, letters, and figures directly over the corresponding ones on the map inserted in his machine, thus making a complete record on perforated tape. On schedule a blank map is inserted in the teletypewriter at each receiving point and positioned so that a type bar will strike the map within the small coordinating circle. The sending operator then releases the tape and the signals transmitted over the circuit reproduce on the map at the receiving stations data similar to those on the original map at the sending station.

The map data are sent in sequence from the two transmitting stations and after they have been received on the map forms a number of duplicate copies can be run off immediately and the two maps fitted together if desired. The maps are then available to pilots at each of the respective airports.

Complete reports of weather are generally maintained

by transport companies in dispatching offices. On some lines two-way short-wave radio-telephone equipment has been provided for communicating with planes and periodic contact is maintained during flight. In this way pilots report their positions directly to dispatchers and in addition supplementary weather data are usually exchanged, particularly in respect to local ceiling heights and conditions in the upper air strata.

Plane Dispatching and Other Service

Teletypewriter circuits furnished to air transport companies are used principally for dispatching planes and handling the many traffic matters usual to this type of service. Plane movements including reports of position in flight are transmitted over the teletypewriter system and recorded at various offices. The reports of positions, in many cases, are given by pilots over short wave radiotelephone where this type of equipment has been provided.

To facilitate position reporting some of the companies have superimposed a system of rectangular coordinates over a map of the course cutting the territory into squares or rectangles 10 to 20 miles on a side. The coordinates are numbered so that the pilots and dispatchers can readily establish the location of the plane. The dispatchers generally maintain a typewritten, chronological log of position reports from each plane in the air. Bulletin boards are also used, marked with the stations along the route and with spaces for filling in data such as plane number and license, name of pilot, time of arrival, and departure at each station and final destination.

A considerable volume of information is required to be transmitted in connection with the handling of traffic on large lines. This usually consists of data as to reservations, number of passengers and amount of mail and express carried, connections to be made, and arrangements at terminals. Supplementary instructions to pilots and many administrative matters requiring prompt handling are also transmitted.

Although the airways teletypewriter circuits furnished the Department of Commerce are used mostly for handling weather reports, considerable information is also transmitted over them relating to departure and arrival of planes and their position in flight. Upon request the Department of Commerce will send over its teletypewriter system the license number of a plane, the station from which the plane is departing, its time of departure, and its destination, to stations along the route of the flight. Stations on the route knowing approximately the time the plane will be due watch for it and record the actual time the plane passes so that other stations may be informed.

Teletypewriter Circuit Layout

The teletypewriter networks furnished by the Bell System for service along airways are composed of some 30 separate circuits. Circuit mileage of the longest is about 2,000 miles and the shortest 200 miles. The longer circuits generally connect 15 to 20 intermediate stations. Since airways naturally follow direct air lines the intermediate airway stations are often located at points considerable distances from main communication lines, which, generally, are constructed along routes connecting the industrial and more populous centers, due regard being given to topographic and other conditions. At the larger airports such as Newark and

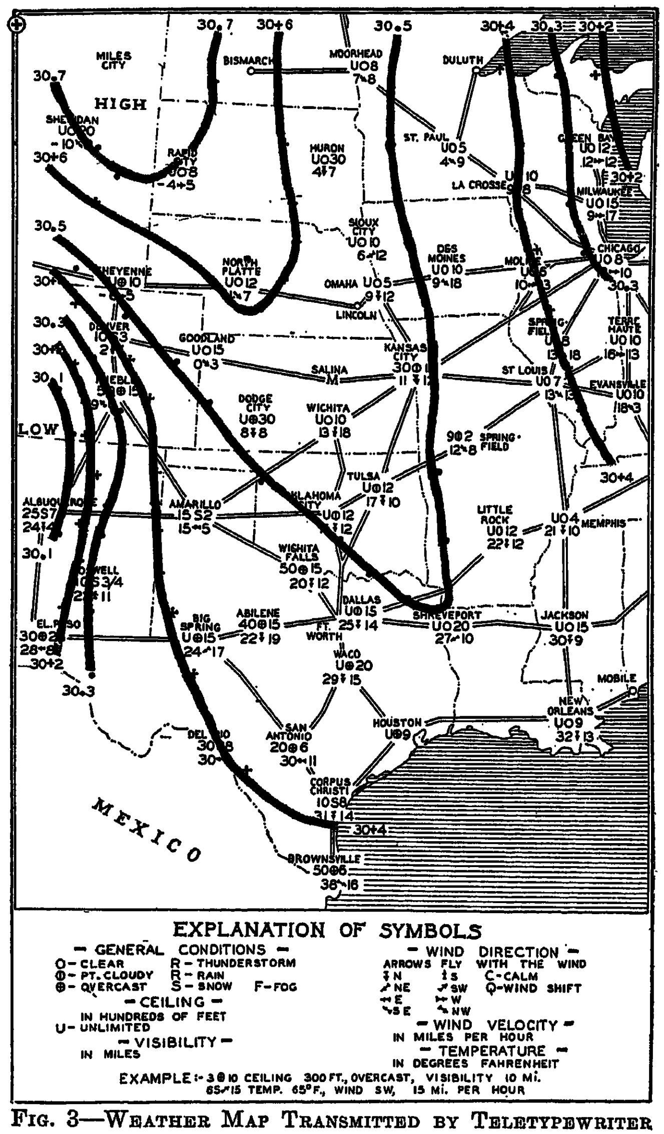

Fig. 3—Weather Map Transmitted by Teletypewriter

Cleveland, local teletypewriter circuits are also provided to connect the Department of Commerce station with the offices of the various transport companies, the post office, and weather bureau. Automatic transmission equipment is provided so that information received on one circuit can be retransmitted over one or more other circuits if desired.

A layout diagram of a typical circuit is shown in Fig. 4. Facilities in the New York-Cleveland long distance cable are used for establishing the main links, totaling 515 miles. Repeater stations on the cable route located

approximately every 50 miles afford convenient points from which branch circuits are extended to the intermediate airway stations. The several branch circuits are of the grounded open-wire type and total 331 miles. A total circuit mileage, therefore, of 846 miles is required in this case for connecting all stations along an air route a little over 400 miles long.

The Newark-Pittsburgh section of the main circuit is operated on metallic telegraph cable facilities, a type particularly adapted to use where stations to be connected to the circuit are spaced at frequent intervals. Between Pittsburgh and Cleveland a channel of a voice-frequency carrier telegraph system on cable facilities is used. This type of facility is generally used where stations are located 150 or more miles apart. The longer branch circuits on open wire employ polar transmission with repeaters at both the repeater station and terminal and use two wires, one for each direction of transmission. The shorter branch circuits use one wire with a grounded duplex repeater at the repeater station and a constant d-c. potential at the outlying terminal. Detail description of these various telegraph systems has been given in previous papers.

Cable circuits are less susceptible than open-wire circuits to interference and storm trouble, and where they are available they have been used generally for establishing teletypewriter circuits furnished both the Department of Commerce and the transport companies.

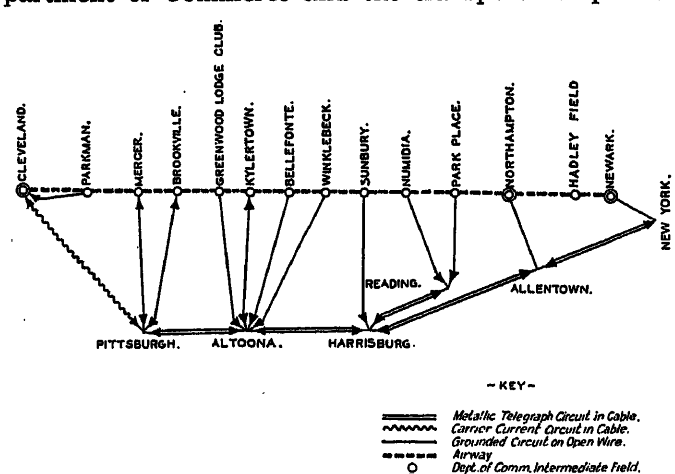

FIG. 4—LAYOUT OF TYPICAL TELETYPEWRITER CIRCUIT ALONG AIRWAY

At present, over one-third of the mileage of these circuits is in cable.

Facilities on alternate routes are available to be substituted for the regular circuit in the event circuit trouble develops. Spare loops to the teletypewriter stations and spare teletypewriter equipment at each station are provided so that each component part of the service is protected by spare facilities and equipment.

TELETYPEWRITER EQUIPMENT

The theory of teletypewriter operation and descriptions of the machines generally used in this country have been given in other papers but are briefly reviewed here in order to describe some of the specific equipment arrangements used in airways service.

The teletypewriter is designed to perform the functions of an ordinary typewriter with added features that permit the typing units of a number of similar machines located at distant points to be controlled by the operation of the keyboard of any one of them. This is accomplished by the translation of the mechanical action of any key in the keyboard unit to electrical impulses arranged in a code and transmitting them over an electrical circuit to the distant machines where the impulses are translated back to the mechanical action of a type bar in the typing unit corresponding to the key struck in the distant keyboard. Electric motors and electromagnets provide the mechanical power and the means of translation of electrical impulses to mechanical action. It is, of course, necessary that the mechanical action of all of the machines be synchronized. This is provided for by the use of synchronous motors or governed motors regulated to the same speed and a start-stop rather than a continuously rotating system. By the use of the start-stop system the effect of variations in motor speeds is minimized, accurate synchronization being required only during the interval of typing of one letter after which a clutch releases and stops the receiving mechanism momentarily to permit it again to start in synchronism with the sending mechanism. To provide the start-stop feature and sufficient code combinations for the letters and symbols required, a seven impulse code is used consisting of a start pulse, five selecting pulses, and a stop pulse.

Teletypewriters are available to print on an ordinary page or on a narrow strip of tape. Tape machines are generally used in airways service because they are particularly adapted to the handling of short messages and weather sequences where it is generally desirable to rearrange the messages received by cutting and pasting the tape on separate pages to form a continuous weather record for each point. This is preferable to a chronological message record requiring a search through all of the information to obtain the trend of weather at a particular point. The tape machines are also somewhat smaller, less expensive, and more efficient, not requiring the transmission of carriage return and paper feeding signals.

In addition to the ordinary sending and receiving machines supplementary apparatus units may be used so that operators can work at maximum efficiency and the line circuit can be used to its maximum capacity. These units are the perforator, tape transmitter, and reperforator.

The perforator is associated with a keyboard and perforates a tape with one to five perforations for each key struck. The tape is run through a tape transmitter which automatically sends electrical impulses to the circuit corresponding to the perforations in the tape and identical to those that would have been sent from the

keyboard direct had it been connected to the circuit for normal keyboard sending. The use of the perforator and tape transmitter permits the circuit to be operated at its maximum speed at all times and permits the operator to work in spurts and rest or do other work while the accumulated tape is running through the transmitter. Also the same tape can be run through several tape transmitters and thus be used for sending the message over several circuits.

The reperforator is a receiving device which records the message on a perforated tape similar to that produced by a perforator unit. This permits storing a received message for immediate or subsequent retransmission to other circuits without retyping it.

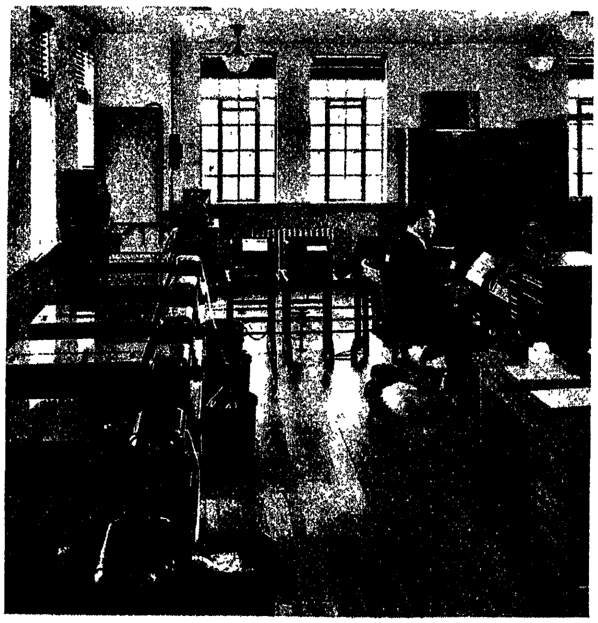

FIG. 5—DEPARTMENT OF COMMERCE TELETYPEWRITER STATION

The smaller teletypewriter stations of the Department of Commerce and those of the various transport companies are each generally provided with a regular and a spare teletypewriter and a small loop switchboard with jacks and cords to connect the regular or spare machine to the regular or spare loop as desired.

At the larger teletypewriter stations of the Department of Commerce a special arrangement of the equipment has been provided to permit efficient operation of the teletypewriter circuits from the standpoints of requiring a minimum number of operators and of obtaining rapid retransmission of messages received on one circuit to one or more of the other circuits as required. A view of an installation is given in Fig. 5 and a typical floor plan arrangement is illustrated in Fig. 6. The apparatus is mounted on tables specially designed for the purpose, and these are usually arranged on the floor in the shape of a U, the units facing inward so that the operators work inside the U.

A separate reperforator A and tape transmitter B in addition to a tape teletypewriter C are provided for each circuit. Messages are received simultaneously on a printed tape by the tape teletyperwriter and on a perforated tape by the reperforator. Mounted adjacent to the reperforators are the tape transmitters through which the perforated tape can be run to retransmit immediately a received message to another circuit. The reperforators and tape transmitters can be started and stopped individually from the remote control box H.

A tape perforator K is provided to perforate tape for messages originating at the local station. The messages can then be sent automatically over the circuit or circuits desired by running the tape through the proper tape transmitters.

All of these units are terminated on cords and plugs at a loop switchboard E and any unit or combination of units may be connected to any of the teletypewriter circuits which are wired through a number of series jacks in the loop switchboard. A supplementary switching arrangement is provided by radial transmitting board G equipped with keys and repeating relays. By operating one or more of the keys one of the tape transmitters can be connected quickly to two or more of the teletypwriter circuits through the repeating relays to obtain simultaneous transmission to the circuits connected.

At certain stations page teletypewriters D are provided for the transmission of weather maps as described previously. This type of machine employs a fixed paper carriage and movable type basket, and accommodates

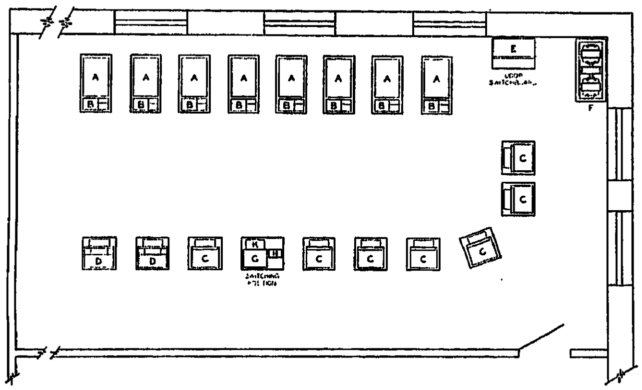

FIG. 6—TELETYPEWRITER EQUIPMENT LAYOUT IN LARGE OFFICE

Legend:
A—Reperforator
B—Transmitter distributor
C—Tape teletypewriter
D—Page teletypewriter
E—Loop switchboard
F—Motor-generator set
G—Radial transmitting board
H—Remote control box
K—Perforator

paper up to 8½ inches wide. It has been equipped with a number of special type characters to provide the symbols required on the maps. These symbols, which are shown in Fig. 3, are provided as upper case characters on the teletypewriters in place of fractions and punctuation marks.

The arrangement of equipment described generally permits one operator to attend all of the circuits. The teletypewriters are all located in a fairly small space,

which permits one man to observe the incoming messages and operate the control boards to start and stop the proper transmitter and to relay the messages as required.

Radio Interference

The establishment of teletypewriter stations along the airways brought about the installation of teletypewriter equipment in the same room or in close proximity to short-wave radio receivers, and introduced the problem in specific cases of radio interference caused by the operation of the teletypewriter.

Remedial measures have been designed effectively to reduce this interference, and consist of the use of synchronous motors, rectifiers, and specially designed filters, together with the locating of the apparatus and wiring in such a way as to effect a minimum coupling between the teletypewriter and its associated loop and the radio antenna system.

Conclusion

History of air transportation in the past few years indicates that continued growth may be expected, particularly as hazards to flying are mitigated and safety and dependability are recognized by the public. The Government is continuing the extension of airways and weather reporting and other services, and air transport companies are progressing in developing transport business. Fast and reliable communication service has proved the backbone of weather and position reporting and has been a valuable aid in the handling of traffic and other matters relating to air transportation. Teletypewriter circuits used for land service have been found particularly suited to meeting the various requirements involving simultaneous communication with many stations at remote distances. Other wire communication services such as long distance telephone and commercial telegraph have also aided, particularly in reaching points not served by teletypewriter circuits. It is expected wire communication service will continue to be used extensively in connection with air transportation and will be of considerable aid in its future development.

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Discussion

H. T. Killingsworth: Cleveland has one of the most important and best equipped airports in the country. Practically all of the features described in the paper are included in the Cleveland communication equipment. The Department of Commerce has five teletypewriter circuits radiating from Cleveland which parallel the more important air routes. One of these extends from Cleveland to Newark and is shown in Fig. 4 of the paper. One parallels the Cleveland-Chicago-St. Louis Airway via Detroit and Kalamazoo. The third extends from Cleveland to Kansas City via Columbus and St. Louis. The fourth extends from Cleveland to Camden via Pittsburgh and Harrisburg and the fifth from Cleveland to Newark via Buffalo and Utica. All of these circuits have numerous intermediate drops at airports along the route.

This equipment is located in the Administration Building at the Airport. The Administration Building is in turn connected by local teletypewriter circuits to the long wave radio transmitting station which is located about one mile away. One of the most common usages of the reperforating equipment in the Administration Building is in connection with retransmitting to the radio station messages which it is felt should be broadcast immediately to planes in flight.

Short wave radio equipment is used by the airport authorities in dispatching planes. The pilot of incoming planes is contacted as he approaches the port, is advised of weather conditions at the field, movement of planes in the vicinity of the field, where to land, at which gate to discharge his passengers, etc. Similarly, a pilot leaving the field is contacted and is directed off the field.

Characteristics of Electromagnetic Radiation from Aircraft in Flight

BY TOM C. RIVES* and JAMES C. COE*

Non-member — Associate, A.I.E.E.

Synopsis.—*This paper reports the results of an investigation of the effects of altitude, frequency and distance upon the strength of a received radio signal as transmitted from an airplane in flight and received at a point on the earth's surface. Frequencies between 475 kc. and 5,500 kc. are reported on for altitudes up to 6,000 feet and distances up to 60 miles. Representative curves, plotted between the above mentioned variables, are included and the difference in results obtained during daylight and darkness are shown. In general, the data show that, within the limits of this investigation, the higher the frequency the shorter the reliable communication range becomes.*

An appendix is included in which is shown how the data for a given altitude, distance and frequency may be used to calculate the theoretical field strength for the given frequency when the transmitter (or airplane) is at a different distance and/or altitude.

Introduction

CONSIDERABLE data have been published giving the characteristics of high-frequency radio transmissions from aircraft to ground for distances over 100 miles but, in general, little definite information is given as to the exact conditions at the time the data were collected. Comparatively few data have been published regarding the transmission characteristics from airplane to ground for distances less than 100 miles. Prior to 1929, aircraft operators made little use of the frequencies above 1,500 kc. Transmission tests on frequencies below 1,500 kc. gave consistent results, in that the field strengths seemed to be subject to a uniform attenuation with distance and were apparently little affected by altitude. The use of the higher frequencies on aircraft is desirable as it permits use of small fixed antennas and more compact and lighter radio equipment on the airplane. In the attempt to use these higher frequencies, freakish results were obtained. So many contradictory data were obtained at the shorter distances that it soon became apparent that a thorough investigation would be necessary before complete advantage could be taken of the higher frequencies.

Plans were made in the summer of 1930 to investigate this subject fully. Master-oscillator type, medium-frequency, 50-watt transmitters were available at that time, and some tests on the medium frequencies were made. High-frequency crystal-controlled transmitters were purchased, and field-strength measuring apparatus obtained. Radio receivers of various types were also procured in order that listening tests might be conducted at the same time as the field-strength measurements were being taken.

Apparatus and Procedure

In the winter of 1931, two types of tri-motored airplanes were obtained for use in the tests. One of these airplanes was covered with fabric and the other with metal. Identical Western Electric 8A crystal-controlled transmitters were installed on each of these airplanes. Fixed antennas of the same dimensions were erected symmetrically over the fuselage and wing sections of each airplane on stub masts approximately 6 feet high. The antenna structure used approximated a horizontal "T," and was fed at the base of the "T." Due to the

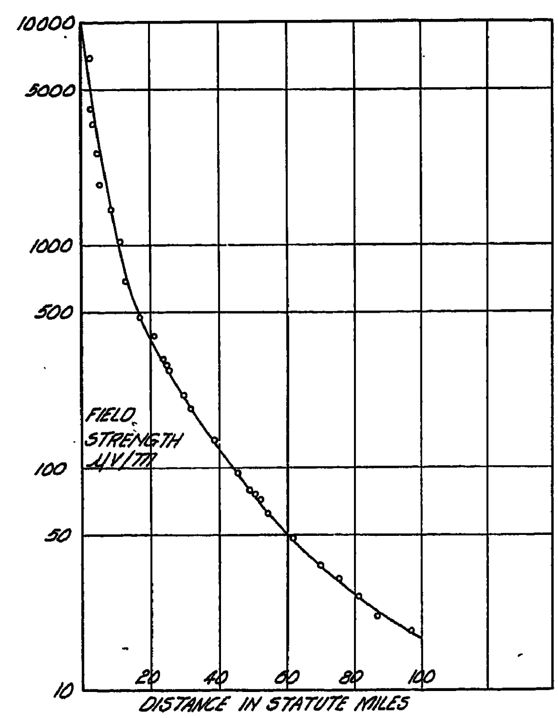

FIG. 1—AVERAGE FIELD STRENGTHS RECEIVED ON THE GROUND FROM A 50-WATT RADIO TRANSMITTER IN AN AIRPLANE

Data—Transmitted frequency, 475 kc.; antenna, trailing wire 194 ft. long; time, 10:08 A.M. to 11:09 A.M., July 31, 1931; course, Indianapolis, Indiana, to Fairfield, Ohio; altitude, 3,000 ft.

wide frequency band covered (1,695 kc. to 5,500 kc.), it was necessary to vary the dimensions of these antennas during the course of the investigation.

A Western Electric type 44A field-strength measuring set was set up in a comparatively level terrain at Fairfield, Ohio. Several radio receivers were set up at

*War Department Signal Corps, Wright Field, Dayton, Ohio.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

selected locations in the vicinity but isolated from each other and the field-strength measuring set.

Two fixed courses were selected for the flights, one from Dayton, Ohio, to Cambridge City, Indiana, and the other from Dayton to Columbus, Ohio. Each course was 60 miles in length. Flights were made over each course at 500 feet, 1,500 feet, 2,500 feet, 3,500 feet, 4,500 feet and 6,000 feet altitude.

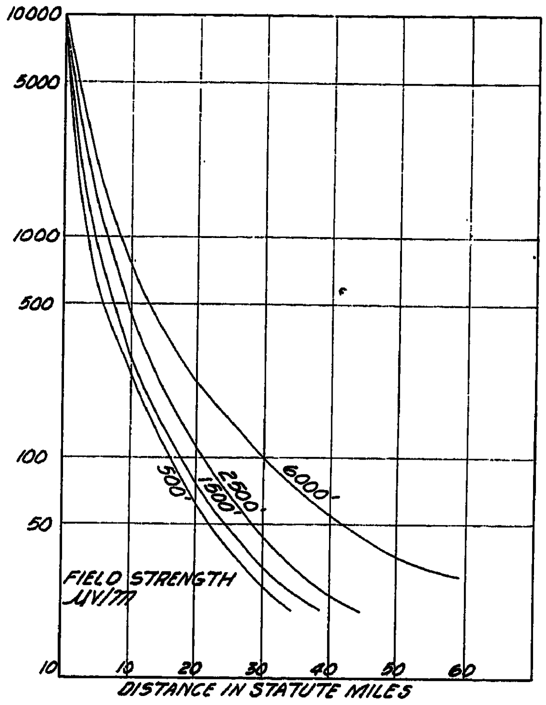

Fig. 2—Average Field Strengths Received on the Ground from a 50-Watt Radio Transmitter in an Airplane

Data—Transmitted frequency, 1,695 kc.; antenna, fixed; time, 9:55 A.M. to 12:30 P.M., March 20, 1931; course, Fairfield, Ohio, to Cambridge City, Indiana; altitudes indicated on curves

The frequencies employed in the high-frequency tests were 1,695, 2,000, 2,495, 3,000, 3,500, 4,000, 5,000 and 5,500 kc. Antenna power was held as near 50 watts as possible on all frequencies.

The two radio operators and the pilot of the airplane were connected by interphone to insure coordination of their work. When the pilot had the airplane on the course at the proper altitude, he notified the first operator. This operator then notified the ground stations of the time and test-run number and thereafter put the carrier frequency on the air for alternate three-minute periods until notified by the pilot that the end of the course had been reached. The second operator kept the meter readings constant by means of the set and power adjustments.

The average speed of the airplane on these test flights was approximately 100 miles per hour. Due to the winds aloft, the airplane speed varied between the limits of 80 and 120 miles per hour. On account of these high speeds, the rate of change of field strength when the airplane was within a short distance of the ground station, was extremely rapid and could not be accurately followed with the field-strength meter.

The field-strength measuring set used was not accurate for measurements of field strengths below 20 microvolts per meter. When fading became severe, it was extremely difficult to secure accurate field-strength measurements. The results shown in the fading zone below the "severe fading line" are the averages for a number of readings taken in rapid succession. The period of the fading was not consistent, on some days being extremely slow and on other days very rapid. Where the curves do not reach the 20 microvolts per meter minimum, it indicates that it was impossible to secure accurate readings due to the rapid and severe fading at that time.

In general, the figures presented in this paper are self-explanatory. A mathematical analysis of these data have been made and is included in the Appendix.

Conclusions

In concluding, it is desired to emphasize that the tests were conducted over one type of terrain and during the

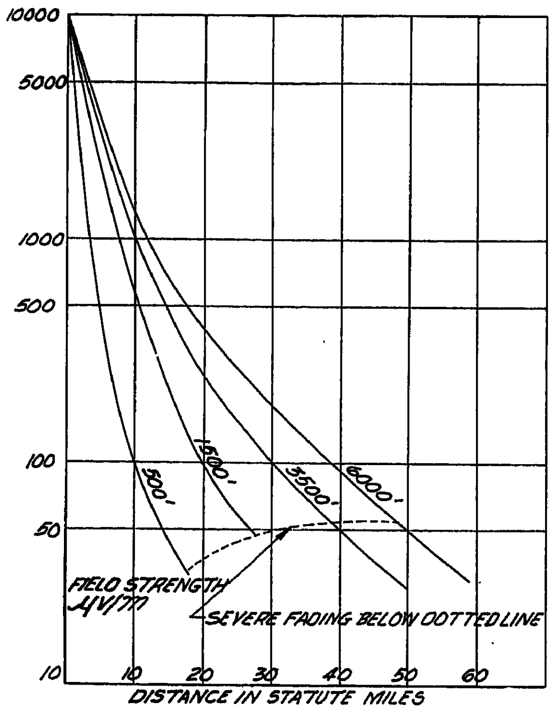

Fig. 3—Average Field Strengths Received on the Ground from a 50-Watt Radio Transmitter in an Airplane

Data—Transmitted frequency, 3,000 kc.; antenna, fixed; time, 1:55 P.M. to 4:50 P.M., April 6, 1931; course, Fairfield, Ohio, to Cambridge City, Indiana; altitudes indicated on curves

winter and spring seasons, with the exception of that shown in Fig. 1, covering the transmission frequency of 475 kc., which was obtained in the middle of the summer. Results of tests conducted over other terrain and during different seasons of the year will no doubt vary from the data given here.

Under the given conditions, it may be stated that:

1. Field strength is dependent upon altitude, distance and frequency.
2. Fading, and not attenuation, is a controlling factor in the use of these frequencies at short distances.
3. Daylight tests show no greater attenuation than is experienced in the night tests.
4. Fading occurs at lower frequencies and shorter distances at night than during the day.

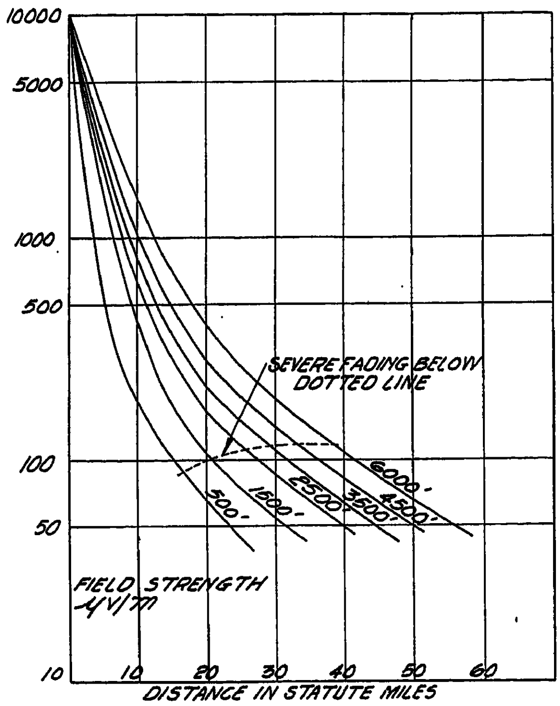

FIG. 4—AVERAGE FIELD STRENGTHS RECEIVED ON THE GROUND FROM A 50-WATT RADIO TRANSMITTER IN AN AIRPLANE

Data—Transmitted frequency, 4,000 kc.; antenna, fixed; time, 11:45 A.M. to 4:14 P.M., March 12, 1931; course, Fairfield, Ohio, to Cambridge City, Indiana; altitudes indicated on the curves

5. Frequencies below 2,000 kc. are more suitable for communication from aircraft to ground for distances up to 60 miles.
6. For any given frequency, the data collected at one altitude and distance may be used as shown in the Appendix to calculate the field strength that will be obtained when flying at another altitude and distance up to the point where fading commences.
7. The similarity of the data obtained when using the trailing wire antenna and when using the fixed antenna indicates that either the field patterns of the two antenna systems are similar or that the difference in field patterns had little effect on the results obtained.

Appendix

LIST OF SYMBOLS

F = measured value of field strength in microvolts per meter.
K = is proportional to the energy radiated in a fixed direction.
f = frequency in kilocycles per second.
λ = wavelength in kilometers.
α' = attenuation factor.
ϵ = 2.718
R = the radius of the earth.
r = distance as measured along the earth.
x = distance as measured along a line tangent to the earth at the receiver.
y = distance the airplane is above or below the tangent line.
ρ = airline distance between the transmitter and receiver.
θ = $\tan^{-1} y/x$
a = altitude as indicated by altimeter.

All distances are in statute miles, unless otherwise stated.

A typical curve of field strength plotted against ground distance is shown in Fig. 8. A curve showing the variation of the angle θ with distance is also plotted on Fig. 8, and where the two curves intersect, the path of the flight intersects the tangent line to the earth. This occurs at zero degrees and 67.4 miles; for greater distances the path of flight is below the tangent for this altitude.

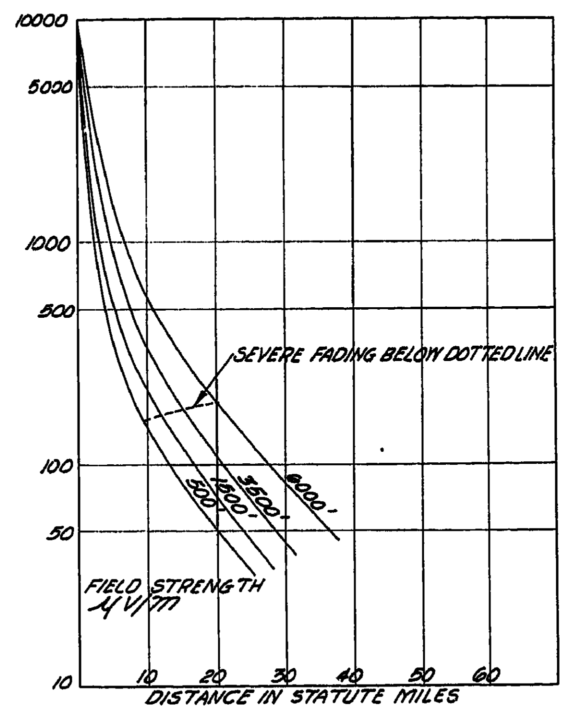

FIG. 5—AVERAGE FIELD STRENGTHS RECEIVED ON THE GROUND FROM A 50-WATT RADIO TRANSMITTER IN AN AIRPLANE

Data—Transmitted frequency, 5,000 kc.; antenna, fixed; time, 8:28 P.M. to 10:53 P.M., April 8, 1931; course, Fairfield, Ohio, to Columbus, Ohio; altitudes shown on curves

The method of increments was used in order to determine if the relationship of field strength to distance was of the form:

$$y = ax + bx^2 + cx^3 + dx^4 \ldots \quad (1)$$

It was found that neither the first increments, ΔF, nor

the second increments, $\Delta^2 F$, nor the third, $\Delta^3 F$ were constant, and there was no indication that any higher increments would be reasonably constant. It was, therefore, concluded that the relationship must be expressed in a form such as:

$$y = ax^{-1} + bx^{-2} + cx^{-3} + dx^{-4} \dots \qquad (2)$$

or as some transcendental function.

If this field strength curve, plotted to logarithmic coordinates, had been linear and expressed as:

$$\log_\epsilon y = m \log_\epsilon x + \log_\epsilon b \qquad (3)$$

then the relationship would have been of the form:

$$y = b/x^m \qquad (4)$$

If that portion between 50 and 100 miles is considered to be approximately linear, then the value of m can be determined by the formula:

$$y - y_1 = m\,(x - x_1) \qquad (5)$$

In this instance m was found to be equal to $-$ 2.32, or the field strength varied with distance to the $-$ 2.32

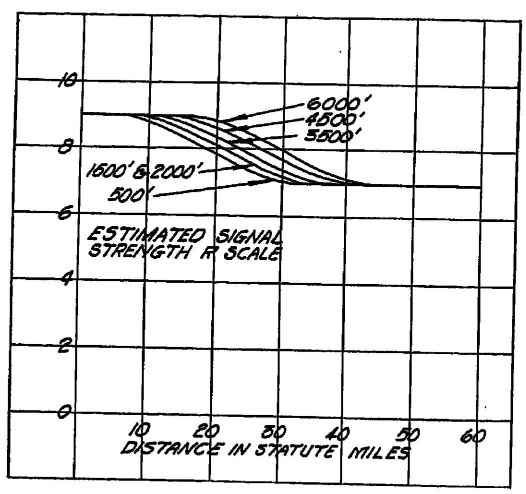

Fig. 6—Average Signal Strengths Received on the Ground from a 50-Watt Radio Transmitter in an Airplane

Data—Transmitted frequency, 2,000 kc.; antenna (on airplane), fixed, (on ground receiver) horizontal, 15 ft. high and 95 ft. long extending N.E. from the receiver; time, 8:20 P.M. to 11:52 P.M. on March 20, 1931; receiver used. General Electric 1496-C

power for these distances. If the curve in Fig. 9 marked "500 ft." is considered nearly linear from 1 to 10 miles, then $m = -$ 1.95, or the field strength varies approximately inversely with the square of the distance.

In order to determine if the relationship was of the form of the Austin formula,[1] the unattenuated values of field strength were expressed as:

$$F' = K/r \qquad (6)$$

then if the measured values of field strength could be expressed as:

$$F = (K/r)\,(\epsilon^{-\alpha' r}) \qquad (7)$$

then the ratio of F' to F is:

$$F'/F = \epsilon^{\alpha' r} \qquad (8)$$

also: $$\log F'/F = \alpha' r \qquad (9)$$

Tabulations made from Fig. 8 of the values of the equations (6) to (9) inclusive and α', show that for ground distances over 15 miles α' remained essentially constant at an average value of 0.0227 for a value of K = 12,800. In Fig. 1 recorded points are shown with a calculated curve having these constants. An equation of the form of (7) fits the data remarkably well, provided that θ is a

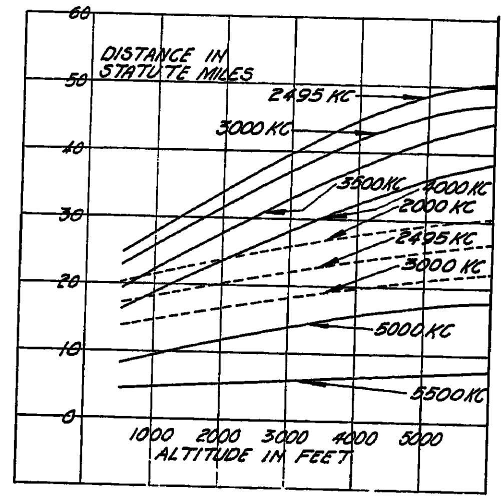

Fig. 7—Average Distances at Which Severe Fading Becomes Apparent in the Signals Received on the Ground from a 50-Watt Radio Transmitter in an Airplane

No appreciable fading was experienced on frequencies other than those shown in figure

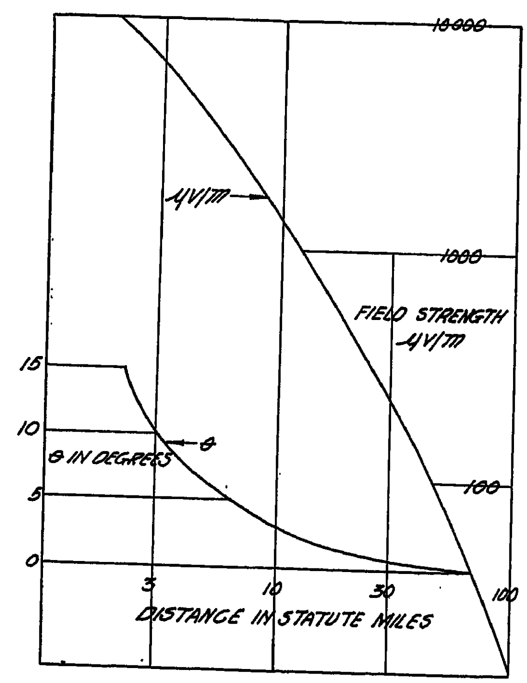

Fig. 8—Curves of Field Strength and θ vs. Ground Distance

The field strength curve is the same as that of Fig. 1 except that log-log coordinates are used for purposes of analysis

small angle, two degrees or less, or when the airplane is below the tangent line.

This procedure was followed for a large number of curves, and families of curves of which Fig. 9 is typical. In no case was it possible to find one value of K and α' which would apply throughout the entire range of distances. In Fig. 9 α' was practically constant for the

1. See Bibliography.

6,000-foot test at 0.0396 for ground distances over 10 miles, with a value of K equal to 18,200. With the value of K determined, values of α' were obtained by a similar process as above except that the angle θ was maintained constant, instead of altitude, giving the relationship:

$$F = (K/\rho)\,(\epsilon^{-\alpha'\rho}) \tag{10}$$

In each case the values of α' decreased as ρ increased, and the product $\alpha'\rho$ was practically constant. This was done for various small angles for the fourteen families of curves, with similar results except in the case of a family of curves taken at 1,695 kc. On the day these flights were made the ceiling was approximately 2,600

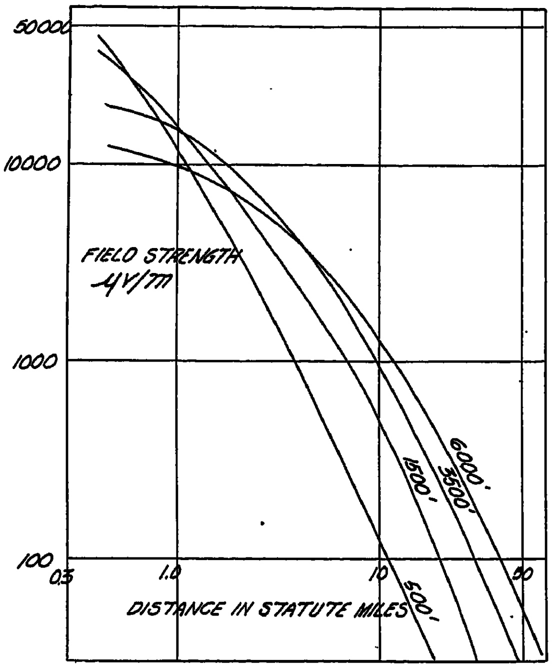

FIG. 9—CURVES OF FIELD STRENGTH VS. GROUND DISTANCE FOR VARIOUS ALTITUDES

These curves are the same as those of Fig. 3 except that log-log coordinates are used for purposes of analysis

feet, and the bank of cumulus clouds extended up to over 5,500 feet above the earth. The 500, 1,500, 2,500, and 6,000-foot flights were made in the usual way, but the 3,500 and 4,500-foot flights, being through clouds, were omitted. The values of $\alpha'\rho$ were approximately 12 per cent higher for the 6,000-foot altitude than for the lower altitudes.

With values of field strength taken at points along a line making a fixed angle to the tangent line:

$$F_1 = (K_1/\rho_1)\,(\epsilon^{-\alpha'_1\rho_1}) \text{ and } F_2 = (K_2/\rho_2)\,(\epsilon^{-\alpha'_2\rho_2}) \tag{11}$$

but $K_1 = K_2$ by definition, and with $\alpha_1'\rho_1 = \alpha_2'\rho_2$ then:

$$F_1/F_2 = \rho_2/\rho_1 \tag{12}$$

or the field strength varies inversely with distance as measured along a line making a fixed angle to the tangent line. This bears out the theory of T. L. Eckersley[2] and the conclusions of Drake and Wilmotte.[3]

From Fig. 9, it is apparent that for very short distances with the particular radiating system used, the field strength decreases with increasing altitudes, and for ground distances of 4 miles or more the field strength increases with altitude. At one mile there is comparatively little change in field strength with altitude. In Fig. 10 (derived from Fig. 9), vertical polar diagrams of field strength for various values of θ are shown, each for a fixed airline distance ρ. The shapes of these curves are determined first, by the values of K which change with θ, and second with α', which is also dependent upon θ. Field strength is practically constant from 20 to 45 degrees. In order for this to be true, $\rho_1 = \rho_2$ of (**11**) so:

$$F_1/F_2 = (K_1/K_2)\,(\epsilon^{-\alpha_1'}/\epsilon^{-\alpha_2'}) \tag{13}$$

or

$$\log_\epsilon (F_1/F_2) = \log_\epsilon (K_1/K_2) + \alpha_2' - \alpha_1' \tag{14}$$

but with $F_1 = F_2$ then:

$$\log_\epsilon (K_1/K_2) = \alpha_1' - \alpha_2' \tag{15}$$

in other words, K and α' must vary in the same sense with variations in θ. As θ is increased, the attenuation and the energy radiated in the direction of the receiver both decrease. For the smaller angles in this particular case, attenuation is predominating factor, while for the larger angles, the directional effect of the transmitting antenna predominates. A complete expression of either field-strength curve of Fig. 8 or 9 must contain terms which take into account the variation of K and α' with

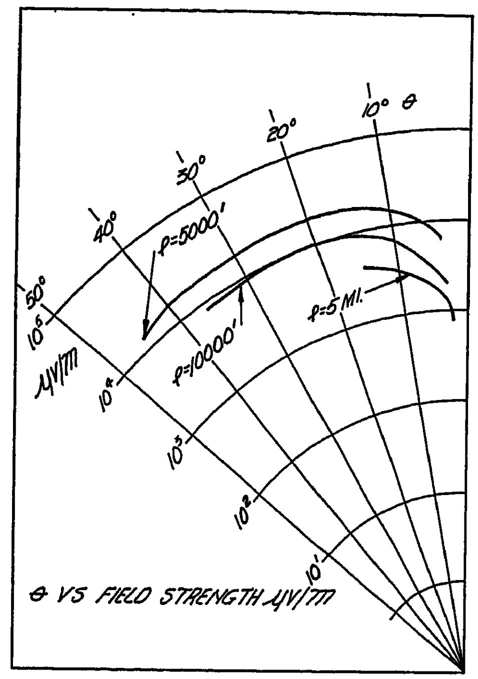

FIG. 10—CURVES OF FIELD STRENGTH VS. θ FOR VARIOUS AIR-LINE DISTANCES

These curves were derived from the same data as Fig. 9

θ. However, it is not necessary to know this expression if it is only desired to calculate the values of field strength for various altitudes and distances, having a curve such as Fig. 8, or one of those of Fig. 9.

In order to find how α' varied with λ, the method of equations (3), (4), and (5) was used and shows that:

$$\alpha' d = \alpha d/\lambda^{0.612} \tag{16}$$

where d is the distance in kilometers. This value agrees with the value of 0.6 given by Austin for wavelengths between 300 and 25,000 meters.

There was no difference between the night tests and the daylight tests, provided that the same conditions obtained as to power, antenna, frequency, altitude, etc., except that the distances free from fading were much less than by day. Since the above calculations are all based on data taken in the non-fading zone, it is not feasible to compute the field strengths where there is fading. It was noted that the dividing line separating the non-fading zone from that in which there was fading, was sharply defined, and followed very approximately a field strength contour. There was a time interval between the instant that an outgoing airplane entered the fading zone, and its emergence on the return flight. This was especially true at night at higher frequencies and lower altitudes.

The results of various tests in which fading was encountered at distances under 60 miles leads to the conclusion that the absorption undergone by the reflected or refracted ray is independent of the angle or distance traveled by that ray. It was noted that in that portion of the fading zone nearest the receiver the effect of the sky ray was to add to or subtract from the field strength measured by day when no fading was encountered at this particular altitude and distance. Since the contour of field strength dividing these zones was at a much higher level at night than by day, it can be concluded that the sky ray undergoes much more absorption by day than night. The decreased distances at which fading occurs as frequency is increased can be explained as being due to at least two causes, namely, the sky rays of the higher frequencies undergo less absorption, while the attenuation near the earth is greater, as shown above.

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4. *Air Transport Communication*, Jones and Ryan, A.I.E.E. TRANS., Vol. 49, January, 1930, pp. 187-197.
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Discussion

A Member: Is it not possible that effects similar to fading could be obtained when flying was rough? It seems as though changes in altitude and direction due to air current would cause a variation in signal strength at the receiver which would resemble fading.

J. C. Coe and T. C. Rives: In these tests we were fortunate in having good flying conditions for the most part, but occasionally when flying was "bumpy" there were slight changes in field strength. Since large tri-motored airplanes were used that were known to be very stable, this effect was very slight. The variation in field strength would be due more to the change in the orientation of the transmitting antenna with respect to the receiving antenna than to an actual change in altitude or distance. In these tests it was found that the fading zone was sharply defined from the zone in which there was no fading.

A Member: According to these curves the distance free from fading depends upon frequency, altitude, and whether day or night conditions obtain; the distance increasing with altitude, decreasing with frequency, and is less at night than by day. What is your explanation of these facts?

J. C. Coe and T. C. Rives: The attenuation undergone by earth-bound rays depends primarily upon distance, altitude, frequency, terrain, and possibly upon the presence of clouds, but in so far as our data are concerned it is independent on whether daylight or darkness obtains. Fading was encountered when the field strength became less than a certain value, this value depending upon frequency, time of day, power, etc. For example, on the 3,000-kc. daylight tests there was fading when the field strength was less than approximately 50 microvolts per meter. At an altitude of 500 ft. there was no fading within 14 miles, while at an altitude of 6,000 ft. fading was not encountered within 47 miles. In each case, and for all altitudes between 500 and 6,000 ft., fading was always experienced when the average value of field strength was less than 50 microvolts per meter. At night, however, fading was encountered at much shorter distances and at correspondingly greater field strengths, namely, at about 125 microvolts per meter; as by day, the dividing line (or surface) separating the non-fading zone from the fading zone, was approximately a field strength contour. It was assumed that this fading was due to the interaction of a sky ray returning from the upper regions which periodically increased and decreased the field strength from the values measured by day when there was no fading at these distances. It was concluded that the average value of the field strength due to the indirect ray was two and one-half times as much as by day in this case, and that the absorption was only about 40 per cent as much at night as by day. Also it was concluded that absorption was independent of angle, altitude, or distance. The decreased distances at which fading occurs as frequency is increased is due to the decreased absorption undergone by the sky rays, and the greater attenuation of the earth-bound rays.

A Member: Was any direct comparison made between different types of transmitting antennas operating on the same frequency in order to determine the effect on field strength and distance free from fading?

J. C. Coe and T. C. Rives: No flights were made which would bring out these facts, although it should be possible to predict the results in a general way. The two most common types of airplane antennas are the horizontal and the trailing wire. For distances so short that the altitude is comparable to the distance, it is difficult to predict just what the results will be due to the fact that the directional effect of the antenna has a predominating effect. Where the distances are greater such that the altitude is not comparable to the distance, the trailing wire antenna would give a greater field strength, other factors being equal. As to the distance free from fading, this would also favor the trailing wire antenna. The horizontal antenna radiates a greater component upward and a lesser component along the earth than a trailing wire having a greater vertical and a lessor horizontal dimension. If this fading is due to the interaction of the returning sky rays with the earth-bound rays the distance free from fading would be greater when using such a trailing wire antenna.

A Member: Using a fixed antenna system on an airplane, would an increase in power change the distance free from fading, providing that the frequency and current distribution remained the same?

J. C. Coe and T. C. Rives: No tests were made from which any conclusions of this nature could be reached. While an increase in power would increase the radiation along the earth, it would increase the radiation skyward a proportionate amount. The answer to this question would be determined by the relative absorption encountered by the sky rays compared to the earth-bound rays. It seems reasonable to assume that the distance at which fading became appreciable would be the same, but at a higher average value of field strength.

Vertically Cut Sound Records

Recent Fundamental Advances in Recording and Reproducing Sound Using Vertical Undulations on a Disk

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and

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Synopsis.—Vertically cut disk sound records possess important advantages over laterally cut records. In their use the recorder and reproducer have been greatly improved. "Cathode sputtering" has replaced graphiting of the wax and a non-abrasive final record has replaced the abrasive record of the past. The improvements which result are:

Noise has been reduced 25 to 30 db.

Volume range has been increased from about 25 or 30 db. to about 50 or 60 db.

Upper frequency cut-off has been extended nearly an octave (to about 9,000 cycles).

The playing time for a 12-inch record may be increased from about 4 minutes to at least 15 minutes.

The life of the record has been tremendously increased.

A more faithful reproduction has been obtained as a result of flatter frequency characteristics and less non-linear distortion so that sounds are more distinct, life-like, and clean cut.

The results demonstrated are enhanced by the use of better microphones and better and, particularly, much more powerful amplifiers and loud speakers than have usually been used before or are now used commercially.

* * * * *

THE phonograph and the telephone were invented at nearly the same time and have grown side by side. The growing knowledge gained in studies of the telephone has aided the phonograph and much of the advance in the phonograph art has been contributed by men primarily associated with the telephone—Bell, Berliner, and Edison. It is of interest in viewing recent advances to review briefly the history of mechanical recording of sound. With both the telephone and the phonograph many devices were tried and many schemes suggested long before success was attained, which, had their proposers possessed just a little more understanding of the problem or a little more persistence and skill in the execution of their ideas, might have been successful.

History of Sound Recording

The recording of sound may be traced back many years. In 1807 Thomas Young described a method of recording the vibrations of a tuning fork on the surface of a drum. The method as described was reduced to practise by Wertheim in 1842. Leon Scott, in 1847, invented the phonautograph, an instrument for the recording of sound which was further improved by König and Barlow, and in 1874 Alexander Graham Bell applied the drum and the bones of the human ear to obtain tracings on smoked glass.

These earlier workers had recorded sound in the form of a wavy line. To Edison goes the credit for making the record in such a form that it could be used to vibrate a diaphragm and thus reproduce sound. Edison's invention was made in 1876, the earliest patent being dated January 1877. The first records were on a cylinder containing a spiral groove, and covered with a thin sheet of tin foil. A steel stylus was attached to a drumhead of gold beater's skin, much like that of Bell's first telephone. The cylinder was rotated and the stylus, moved by the vibrations of the diaphragm, pressed a groove of varying depth into the tin foil. The same device if allowed to again traverse this groove would reproduce the sound.

Bell and Tainter later studied the various methods and concluded that the rubbing process should be abandoned and an engraving process substituted; that is, instead of pushing the record surface down in a spiral groove as in the original phonograph, it should rather be dug out or engraved. As a result of their work they obtained a patent on such a device in 1886, and in 1887 produced the graphophone—the first really practical apparatus of the phonograph type. A critical comment made at the time, however, stated that "the reproduced sound is as loud as that of a good telephone conversation but the distortion is sufficient to make the voice unrecognizable save to a strained imagination added to a previous knowledge of the author of the voice."

The record of this machine was a thin pasteboard cylinder covered with wax. Following this, Edison abandoned the tin-foil type of record and adopted the wax cylinder with an engraving process. In 1887, Emile Berliner patented the gramophone. Berliner concluded that the forces required to cut a groove of varying depth were much greater than those available from the human voice without great distortion of the motions involved. He therefore returned to the earlier ideas of Young, Scott and König, and proceeded to make a lateral record. He concluded in addition that it would be much more convenient if these records were in flat or disk form. It is of interest that Edison in his first disclosures also describes the use of a disk, although he apparently did not consider it practical and abandoned the idea.

Berliner engraved his records on metal disks covered with an extremely thin layer of wax. He tried also a mixture of lamp-black and oil to form "a fatty ink which, when crossed by a stylus, shows even under a

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microscope, a sharply cut transparent line." He recorded with the disk placed above the recording stylus so that any dust that was formed would fall away. Having thus removed the wax or ink from the surface of the metal, he then etched the disk chemically. The lateral type disk record of Berliner has since been greatly developed and improved and has been the most commonly used commercial type of record for about forty years. The very early commercial records which were sold were all original recordings. Subsequently these were copied by playing from them onto other records; that is, by re-recording. About 1900, Edison rendered the original waxes conducting by sputtering or evaporating gold onto the wax at high voltage in a vacuum. About this time also, very fine graphite began to be used to render the original wax conducting. A stamper was plated from the conducting wax and from this a thermoplastic final record was then pressed.

During these early years, many other methods of storing sound were tried. Some of these were optical, some mechanical. For successful operation, however, all of these methods required both a facility in the design and use of vibratory systems and devices not then available.

Electrical recording was often suggested and tried by the various phonograph companies, but in general without much success because of the lack of a satisfactory amplifier. Researches and developments in the communication field paved the way for this application, and development studies were carried on by Bell Telephone Laboratories for a number of years. These reached the point of commercial application in 1924 and a number of companies was licensed to use the improved methods which have now practically displaced the earlier methods in which recording and reproducing were both carried out entirely without electrical means. In 1926 essentially these same methods were extended to the field of sound pictures.

Since that time, although there has been continued development, no outstanding changes or improvements in disk records have been reported until recently. These continuing investigations have now led to considerable further advance. A highly satisfactory process of cutting and of processing records, and of reproducing from them, has been developed. This will be described and demonstrated.

Problems to Be Solved

Reproduction from disk records of the past has failed in several ways to meet all requirements either for reproduction in rooms, as in the home, or in large halls or theaters. The most serious fault has been the noise often referred to as "needle scratch" or "surface noise." Other shortcomings in their order of importance have been failure to reproduce all components over a broad frequency range particularly the higher frequencies and failure to reproduce an adequate range in loudness, due principally to inability to reproduce weak sounds. This has been caused by masking of weak sounds by surface noise. Next in importance has come distortion due to inability of the reproducing needle to follow the record groove accurately. This has been more marked with loud sounds of certain frequencies and has been a minor cause limiting the volume range. The playing time for a record of reasonable size has been rather inadequate and finally the record life has been too short for some otherwise possible applications.

These different characteristics are closely related. Improvement in one is apt to help the others. Consideration of all these problems has come to indicate strongly the desirability of using a vertically rather than a laterally undulating groove.

Surface Noise

Frequency analyses of surface noise have been made using a variety of reproducers and record materials. In general, the shapes of these frequency characteristics have been found to be very largely influenced by the resonance characteristics of the reproducers whereas the amount of noise is dependent on the record. They do not show any marked differences as between lateral and vertical recordings. Frequency charts of surface noise taken with a vertical reproducer having a very flat frequency characteristic over the audible range have shown the surface noise to be relatively richer in high frequencies. The distribution of energy below 10,000 cycles for a cellulose acetate pressing is shown in Fig. 1. The amount of recorded sound energy in the low frequency range (that is, below about 2,000 or 3,000 cycles) is, however, large relative to that in the higher frequency ranges. Moreover, the characteristics of many lateral reproducers have been such as to accentuate surface noise between 3,000 and 5,000 cycles. Obviously, therefore, the elimination of the higher frequency components of the surface noise must cause a large reduction in such noise without any material reduction in loudness of the sounds of interest. Such elimination of the higher frequencies has another effect which for much commercial work has been of very practical importance. It greatly reduces the audible distortion due to poor recording, poor tracking, overloaded amplifiers, etc. It may serve to give a passable result without the expense involved in a thoroughly high grade system. Although the loss of the desired higher frequencies is serious, it has been held by many that the net result has justified the practise. Such low-pass filter systems, usually of very simple and crude design have been commonly known as "scratch filters."

Surface noise is caused by a more or less random dis-

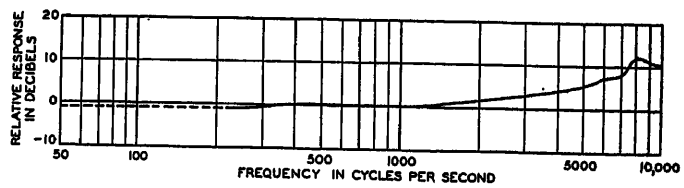

Fig. 1—Energy Distribution of Surface Noise from a Cellulose Acetate Record

tribution of impulsive shocks on the needle due to minute irregularities in the record. It has been common practise in lateral recording to use record material containing a certain amount of abrasive in order to grind the needle to fit the groove. The irregularities due to the abrasive would logically be expected to produce a scratchy noise of the character with which we are all familiar. A 5,000-cycle note of the same loudness as a 10,000-cycle band of surface noise from the records whose development is described here, using a reproducer with a flat characteristic, would have a displacement amplitude of only about 0.000001 inch. In order to reduce the surface noise to the point where it is no longer troublesome, it is necessary to eliminate irregularities at least down to this order of magnitude. It has been found that if the usual abrasive record is replaced by an unabrasive record pressed of a very clean homogeneous material such as cellulose acetate, the surface noise caused by the record material itself is greatly reduced. Such a change, however, by itself has been found to give a comparatively minor improvement, for when the noise due to the record material is moved well into the background, other causes of surface noise of nearly the same order of magnitude as that due to the abrasive of a shellac record become controlling.

The next process which it has been found necessary to improve has been that for rendering the surface of the original wax electrically conducting. This is necessary

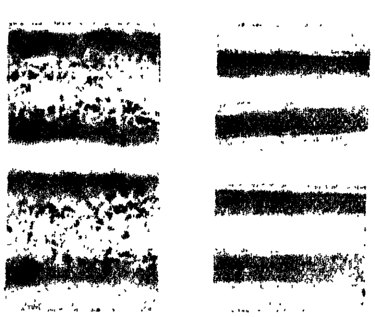

FIG. 2—RECORD GROOVES AS SEEN UNDER THE MICROSCOPE

Left, graphited grooves. Right, sputtered grooves. Note: The microscope is focused on the bottom of the groove

in order that the wax may be electroplated to provide a negative with which to press the final record. The usual methods of graphiting or brushing with fine electrically conducting powders have been found unsatisfactory since the individual particles are reproduced in the plated matrix and also the pressed record, thus introducing noise. In addition the brushing of the wax tends to injure its delicate surface. Recourse has therefore been had to one of the earlier methods used in phonograph practise; namely, cathode sputtering[1] of the wax. Fig. 2 shows graphited and also sputtered groove surfaces as seen under a microscope. By using a very thin layer of wax flowed onto a metal surface it is possible to keep the wax cool, thus simplifying the sputtering operation. It is thus possible to apply an extremely uniform, smooth and tenacious surface of metal of adequate thickness in a very few minutes. This can be electroplated by the ordinary methods and used to press the final record. By the use of this thin flowed wax, it is possible to obtain a surface texture which is extremely smooth, homogeneous, and free from the mechanical strains incident to shaving the waxes by the methods previously used. In addition, waxes of this type possess obvious advantages in ease of transportation, sturdiness, etc.

These improvements in the methods of engraving, processing, and in the final record material are more or less applicable to either type of recording, lateral or vertical. However, the non-abrasive record calls for a permanently shaped stylus point. There has appeared to be less difficulty in providing this with the vertical record. Full advantage can, however, only be taken of the inherent quietness of the records described above if the frequency range is extended to the full extent made possible. In amount the reduction in surface noise from that of present commercial records will differ depending on the frequency range reproduced.

The surface noise of the new record when reproduced with a 10,000-cycle band of frequencies if compared with the old record reproduced with a 5,000-cycle band of frequencies, which is the comparison of practical interest, shows a reduction in noise of about 15 db. In addition, it is possible to take advantage of the fact that most sounds to be recorded contain less energy in the high frequency range than in the medium or low frequency range[2] and therefore to record the higher frequencies at somewhat higher than normal level. In reproduction these higher frequencies are, of course, attenuated relative to the lower ones by the proper amount in the reproducing amplifier or circuit. It is thus found that a further reduction of about 10 db. in surface noise can be obtained, the amount depending somewhat on the high frequency cut-off of the reproducer or circuit. This effect is chiefly between 5,000 and 10,000 cycles.

Extension of Frequency Range

The extension of the frequency range for the recorder is a straightforward problem in design of vibratory systems. With the reproducer the problem is one of designing a system which can be accurately driven by the undulations of the groove without undesirably large forces being set up such as would injure the record. To a considerable degree this is a problem in reducing the mass of its vibratory system. This has been found easier with the vertical system. With vertical recording and reproduction the overall frequency range has been extended thus far to about 9,000 cycles.

Volume Range

The volume range for any particular frequency band is usually considered to be the difference in db. between

1. Günther Schulze, "Cathode Sputtering," *Zeitsch. f. Physik*, Apr. 1926, Aug. 1926.

2. "Speech and Hearing," by H. Fletcher, D. Van Nostrand, 1929.

the loudness of the surface noise and the loudness of the maximum recorded sound which the record can accommodate when reproduced faithfully over this frequency range. The volume range of the lateral records of the past when reproduced to 5,000 cycles may be stated as about 25 to 35 db. With vertical recording the volume range for a 5,000-cycle band of frequencies is 55 to 60 db. For 9,000-cycle reproduction the volume range is 50 to 55 db. This is very important in reproduction in large halls or theaters where an amplifier and loud speaker of adequate power capacity must be assumed. For reproduction in the home a smaller volume range may be preferred. For such home reproduction these vertical records should prove practically noiseless.

Accuracy of Tracking

In addition to the limitations imposed by surface noise, it is evident that, with the available reproducers for lateral cut records, the needle point may fail to follow the center of the groove accurately when the curvature becomes too sharp and may skid from side to side by varying amounts depending on the record and the characteristics of the reproducer being used. Studies have proceeded relating to the physical characteristics necessary in a reproducer in order that it may faithfully follow a groove. These studies have led us to expect superior performance from a groove cut with vertical undulations to that from one with lateral undulations. With the lateral groove there is distortion due to the fact that the sound is recorded with a chisel shaped stylus and reproduced with a round stylus, also that in reproduction the bearing point of the stylus against the groove shifts forward and backward as the needle rounds a curve. With vertical records the first of these effects, sometimes called the "pinch" effect, is absent but a shifting of the bearing point of the reproducing stylus forward and backward occurs if a round tipped stylus is used. For a given stylus tip radius and for a given recording level this effect increases with frequency.

This failure of a stylus point to follow a vertical record with full accuracy is, of course, due to the finite width of the stylus point along the groove and is somewhat analogous to the slit width in optical reproduction from a film. The fact that speech and music and most of the other sounds which it is of interest to reproduce contain much less energy in the high than in the low frequency range so that the shifting of the bearing point along the groove is considerably less than if relatively more energy were present at the higher frequencies, tends to relieve the situation.

Lateral and vertical records drive the reproducer point quite differently. Lateral records drive the point symmetrically from both sides but the point rarely follows the center of the groove with entire exactitude. It deviates from the center by amounts chiefly dependent upon the mechanical impedance of the reproducer. A vertically cut record, on the other hand, drives in only one direction. The restoring force is due chiefly to the elasticity of the supporting structure of the reproducer, the normal restoring force being equal to the total weight on the needle minus the weight of the moving or vibrating part. The stylus point will always remain in contact with the record unless the forces set up by the record undulations exceed this normal restoring force. Operation should always be below this limiting condition. This sets definite requirements on the mechanical impedance of the vibrating parts and, unless this condition can be met, reproduction of extreme frequencies by vertical records is impossible. With the vertical reproducers which we have used, however, the stylus can follow sudden downward motions of the record groove even to accelerations greater than a thousand times that due to gravity. With lateral records there is no definite limiting condition analogous to the above. However, it appears easier in practical design greatly to reduce the mechanical impedance for vertical than for lateral reproducers. Practical experience has shown that the mass of the vibratory system of a vertical reproducer can be so reduced as to reproduce up to well above 10,000 cycles and the stiffness reduced so as to reproduce down to the order of 20 cycles. In fact, there appears to be considerable margin on this score.

Lateral records have usually been cut with a stylus having a tip radius between 0.002 inch and 0.003 inch. The angle between the two sides has, in this country, commonly been about 90 degrees. The groove has been 0.002 inch to 0.003 inch deep and about 0.006 inch to 0.007 inch wide. The groove spacing has been 0.010 inch to 0.011 inch so that the uncut space between blank grooves has been 0.003 inch to 0.004 inch. If one groove is not cut over into the next, the maximum amplitude which could be used has been limited to about 0.002 inch. If the usual loudness of the record is to be maintained it is necessary to maintain this spacing between grooves.

With vertical records it has been found desirable, particularly where a very loud record is to be made, to use a recording stylus with approximately the same tip radius as used previously with lateral, but to reduce the divergence between the sides of the stylus above the tip. In addition it has not been found necessary to provide any clearance space between grooves. It is therefore feasible to increase the number of grooves per inch from the usual 98 to between 125 and 150 and at the same time to raise the recording level. When using this recording stylus with the lesser divergence to cut a record with 125-150 threads per inch it has been found desirable to make the normal unmodulated groove about 0.007 inch wide and about 0.003 inch deep. The maximum amplitude may, under these conditions, be increased about 4 db. It has been found possible, however, to obtain satisfactory results with most waxes even though the normal depth of the groove is increased to as much as 0.004 inch to 0.006 inch. In this case, the recorded level may be increased 6 db. This increase in the record-

ing level obviously increases the volume range by a like amount. If occasionally, due to a loud crash of sound, the recording stylus completely leaves the wax, the reproducer will still continue in the right groove. The corresponding situation with a lateral record where one groove cuts into another is, of course, fatal since the reproducer will usually cross into the next groove in such a case.

Playing Time of a Record

It has been found desirable with vertical records to use a permanent reproducing stylus in order to reduce the vibrating mass of the reproducer to a satisfactory value. This stylus point remains sharp in contrast with the steel needles used with lateral records and therefore will reproduce satisfactorily for undulations of sharper curvature. In other words, over the same amplitudes the linear speed of the record may be reduced. Practically, it may be undesirable to reduce or change the rate of rotation of a record from what has been commercially in use in theater reproduction. It is, however, feasible to decrease the internal groove diameter recorded on such a 33⅓ r.p.m. record to about 6 inches. By the combination of the various elements mentioned above, it has been found feasible to record for 15 to 20 minutes on a 12-inch record and for 10 to 12 minutes on a 10-inch record. This involves the use of about 200 grooves per inch and a decrease in the recorded level to about the level of laterally recorded records using 98 grooves per inch. Of course, longer recordings can be made in the same space if the recorded level is decreased (more grooves per inch), or if the upper frequency cut-off is decreased (decreased r.p.m. and inner diameter). If only speech or music of small volume range are to be recorded it is feasible to make each face of a 12-inch record play 30 to 40 minutes. However, such changes may introduce tracking difficulties if carried too far and must be well justified by other considerations if carried beyond these limits.

Record Life

The great reduction in the mass and stiffness of the vibrating system of vertical reproducers discussed above makes it possible to reduce the weight with which the reproducer point bears on the record to between 2 and 20 per cent of that which has been used with most commercial lateral reproducers. This reduction in stylus or needle point pressure has been found to decrease the wear on the record very greatly with the result that its life has been vastly increased. Tests have shown that the first few thousand playings cause negligible deterioration and even several hundred thousand playings do not show excessive wear if the record is properly protected from dust and dirt.

The Reproducer

A reproducer for vertically cut records which uses a coil of wire vibrated in a radial magnetic field has been found highly satisfactory. Such a reproducer is simple and sturdy. Its performance is linear over a wide amplitude range; it may be made extremely light and, at the same time, is quite efficient. The coils used have had a diameter of between 0.08 inch and 0.2 inch and the total mass of the vibrating system including the diamond or sapphire stylus has varied with different models from 5 to 35 milligrams. The total force on the record has been reduced from about 150 grams to between 5 and 25 grams, the lighter structure being used when playing from a soft wax. With the larger of these designs it has been found possible to obtain efficiencies which are comparable with the efficiency of the Western Electric oil-damped reproducer used with lateral records. No difficulty has been experienced due to failure to follow the groove if these are mounted on a simple pivoted arm as for lateral reproducers. Due to their very small mass they operate quite satisfactorily even though the record turn table fails to operate in a true plane and though the record be considerably warped.

The response of the moving coil vertical reproducer is practically constant over a very broad frequency range. A typical response characteristic is shown in

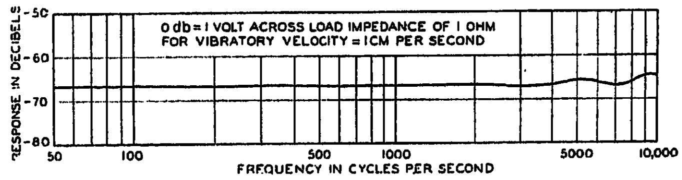

Fig. 3—Response Frequency Characteristic of an Experimental Vertical Reproducer Driven by Cellulose Acetate Records

Fig. 3, which is a characteristic taken with cellulose acetate pressings.

The Recorder

The design of a recorder for vertical records involves no fundamentally new problems over lateral type recorders which have been described previously.[3] It is still desirable to design the recorder to approximate constant amplitude characteristic for the lower frequency range and constant velocity for the higher range. The same type of recorder which has been used for lateral recording can be converted for vertical recording by the addition of a comparatively simple link system. With a few changes in the masses and stiffnesses of the parts it may be given a quite acceptable frequency characteristic. Such a recorder has been used in making the records which will be demonstrated. Its frequency characteristic is shown in Fig. 4.

Reproducing System Characteristic

The response of the oil-damped lateral reproducer is highest at the very low frequencies. Its response de-

3. *High Quality Recording and Reproducing of Music and Speech*, by Maxfield and Harrison, A.I.E.E. Trans., Feb. 1926.

creases with increasing frequency, this decrease in the higher frequency range more or less compensating for the increase of response with frequency of the recorder. Because of the flat characteristic of the vertical reproducer, it has been found desirable to compensate in the reproducing amplifier or circuit for the low response of the vertical recorder at the lower end of the frequency

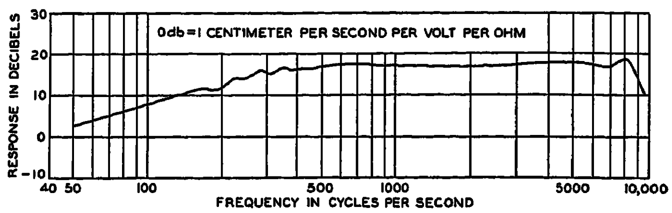

FIG. 4—RESPONSE FREQUENCY CHARACTERISTIC OF AN EXPERIMENTAL VERTICAL RECORDER

scale. A frequency characteristic for the combination of recorder, reproducer, amplifier, and network is shown in Fig. 5.

It has been found with vertical records that speech is reproduced with considerably improved naturalness and that the word endings, sibilant sounds, etc., are much more distinct. The sounds from the different instruments in an orchestra, even when playing a loud passage, are reproduced with very great individuality and clarity. Results of this sort are difficult to describe and should be heard to be fully appreciated. If records such as those described are reproduced using various low-pass filters, the elimination of frequencies even above 7,000 cycles is easily noticeable. On the other hand little or no difference in needle scratch or surface noise may be observed, this being almost wholly absent in most cases, whether the records contain speech or music or if blank grooves be reproduced. In listening to these

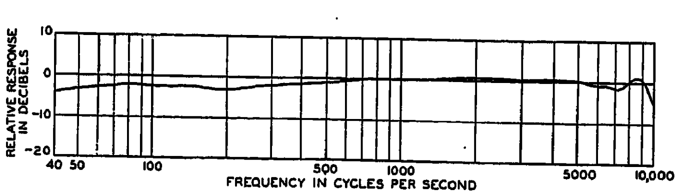

FIG. 5—OVERALL FREQUENCY RESPONSE CHARACTERISTIC (RECORDER + REPRODUCER + NETWORK + AMPLIFIER)

records a loud speaker has been used which is essentially flat over a large portion of the range of audibility, its characteristic being as shown[4] in Fig. 6. The moving coil microphone has been used[5] in making records by this process.

4. "An Efficient Loud Speaker at the Higher Audible Frequencies," L. G. Bostwick, *Jl. Acoustical Society of America*, Oct. 1930.

5. "A Moving Coil Microphone for High Quality Sound Reproduction," by W. C. Jones and L. W. Giles, *Proc. S.M.P.E.*

Discussion

Benjamin Olney: A question sometimes raised after the demonstration of a system of this kind is: How does the performance compare with average radio broadcast reception? The question is of interest because of the wide acceptance of radio as a means of home entertainment; the answer must conclude that the quality delivered by the present system is greatly superior to that of radio reproduction. The reason for the poorer quality of radio reception is not because means for bettering it are unavailable, but because of certain practical limitations which prevent the application of known remedies.

Aside from electrical and mechanical difficulties, an essential acoustical requirement for the reproduction, by a home radio receiver, of frequencies as low as those you may hear in the present demonstration, would be the mounting of the loud speaker in a cabinet or panel comparable in size with the one before you. This, obviously, would be difficult in the average home and constitutes the principal limiting factor to low frequency reproduction.

On account of the spacing of radio channels 10 kilocycles apart in the ether, it is necessary that an adequately selective radio receiver reject frequencies above 5,000 cycles. In the practical case, it is not feasible to secure a sharp cut-off at 5,000 cycles, so the response of even high-grade receivers falls off rapidly somewhere between 4,000 and 5,000 cycles. Some sharply selective receivers may reproduce very little above 3,000

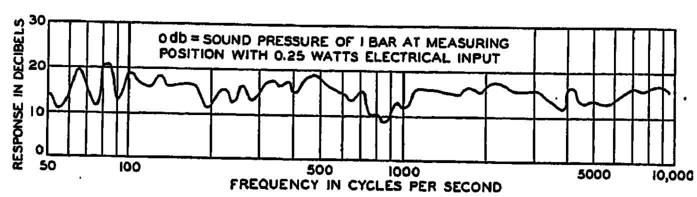

FIG. 6—RESPONSE FREQUENCY CHARACTERISTIC OF COMBINED HIGH AND LOW FREQUENCY LOUD SPEAKERS

cycles, and many sets are provided with a hand-operated "tone control" by which it is possible virtually to eliminate frequencies above about 1,500 cycles.

Laboratory model receivers whose overall frequency range extends up to 7,000 or 8,000 cycles are found to reveal defects in broadcast station modulation which are inaudible with an ordinary receiver. In addition, there is the expected increase in background noise which accompanies an extension upward of the frequency range.

The volume range displayed in the present demonstration is, of course, much greater than is had with radio receivers, due not only to the limitations of the receiver itself, but also to those of the broadcast transmitter and associated telephone circuits.

It appears that, in order to obtain a high frequency range in radio reception comparable to that given here, the following steps will be necessary aside merely from extending the frequency range of both the radio receiver and the broadcast system:

1. The frequency spacing of adjacent broadcast channels must be at least doubled.

2. The effective power of many stations must be increased so as to provide a greater signal-noise ratio.

3. Carbon button microphones must be used with caution, if at all, because their "carbon hiss" becomes very apparent in systems reproducing the higher frequencies.

4. Over-modulation of broadcast transmitters must be avoided to a much greater extent than at present.

It will thus be seen that fundamental changes must be made in the present radio broadcast system before a frequency range may be enjoyed that is comparable with that afforded by this highly developed recording and reproducing system.

Adequate Wiring of Buildings, an Essential for Good Illumination

BY G. H. STICKNEY* and WALTER STURROCK*
Fellow, A.I.E.E. Non-member

PROGRESS in securing good illumination in buildings has, within a few years, been seriously impeded by lack of sufficient wiring capacity, much to the disadvantage of owners and managements. This paper reviews the situation from an illuminating engineering standpoint in the hope of stimulating engineering interest in the problem and thus promoting wider exemplification of practises which will insure reasonable prospect of adequacy of lighting circuits to facilitate proper illumination during the life of a structure. No attempt is made to cover applications other than illumination, except so far as they are fed from lighting circuits and thus affect the illumination results.

ILLUMINATING ENGINEERS AND LIGHTING PRACTISE

For the rank and file of ordinary lighting installations such as small stores, work shops, and offices, rather definite rules have been evolved. In fact, these rules have become sufficiently definite as to constitute practises from which the requirements, which lighting imposes upon the wiring, may be predicted within reasonable limits. Contemporaneously with the development of lighting practise there has come into existence a group of illuminating or lighting service engineers associated with the electric utility companies, leading lamp and equipment manufacturers, and some of the large users of light, who, largely through the medium of the Illuminating Engineering Society, have interchanged data and experience with each other as well as with practising consultants.

A large measure of the effort of these engineers has been devoted to the repair and correction of lighting installations, which, for one reason or another, have proved unsatisfactory in operation. They have, therefore, had an unusual opportunity of determining the border lines of satisfactory and unsatisfactory lighting. It is this experience, embodied in the criteria and rules for lighting practise which has rendered the practise so reliable and secured its wide acceptance. While this experience has been dominantly with the smaller installations, in which, for economic reasons, paid consultants are not usually retained, it should be borne in mind that the more elaborate installations have at least as stringent requirements.

The lighting practises, referred to, have been expressed in papers and reports before various associations. Notable among these are the lighting codes of the Illuminating Engineering Society, the American Standards Association, and the International Commission on Illumination. The accepted illumination levels for the most common conditions of building lighting have been compiled in tabular form by leading illuminating engineers. Among other places these tables have been published in the Franklin Red Seal Specification of the Society for Electrical Development, which also prescribes approximate rules for the lighting design of the simpler and more common classes of building interiors. Without recommending the use of these rules beyond their intended scope, it may be pointed out that the fundamental characteristics of illumination upon which the specification is based are representative of good lighting practise as referred to herein. This specification is probably the simplest, most condensed and most comprehensive expression of present lighting practise; it thus furnishes a reasonable expression of the electric power requirements of that practise.

LIGHTING PRACTISE ADVANCING

While, as has been pointed out, electric lighting practise in the more common applications is comparatively definite, it is not static. Illumination levels, that is to say the quantitative elements, have been rising steadily for many years and except for the retardation during periods of business depression, there is no indication that most fields have approached saturation. Moreover, there is an increasing demand for diffusion and reduction of glare, which is generally secured at a sacrifice of light, and, therefore, puts an additional requirement on the amount of electricity to be supplied.

While qualitatively these advances are generally recognized, it is exceedingly difficult to secure any quantitative measure for them. Since the advances are the resultants of various forces, some peculiar to the application, the locality, the time, etc., it follows that they are variable and cannot be simply expressed. Probably the best authoritative examples are illustrated by the illumination values for the industrial lighting field as published in the 1921 and 1930 issues of the "American Standard Code of Lighting for Factories, Mills and Other Work Places."[1] The two issues give the values in different form and in some instances different classifications. However, a few samples have been selected, on the basis of diversity of interest, and incorporated in Table I to facilitate a numerical comparison. It is probably that in most instances the advances are, if anything, greater than here indicated as the later

*Incandescent Lamp Dept., General Electric Co., Nela Park, Cleveland.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

1. For references see Bibliography.

values were presumably more widely exemplified in actual installations at the time of issue. It seems safe to say that, in general, the decade ending in 1930 witnessed an approximate doubling of light requirement for good practise in the principal classes of commercial, industrial and office lighting.

TABLE I—ILLUMINATION LEVELS GOOD PRACTISE
A few representative examples extracted from American Standard Code of Lighting Factories, Mills and Other Work Places, Issues of 1921 and 1930

Class of Operation or Interior	Foot Candles 1921	Foot Candles 1930
Assembly—Rough	2 to 5	8-5
—Medium		12-8
—Medium fine	5 to 10.	
—Extra fine	10 to 20	100-25
Chemical works—Hand furnaces, etc.	2 to 5	5-3
Cloth products—Light goods	5 to 10	15-10
—Dark goods	10 to 20	100-25
Elevators—Freight and passenger	2 to 5	8-5
Forge shops	2 to 5	10-6
Foundries—Charging floor	2 to 5	8-5
—Fine molding and core making	5 to 10	15-10
Glove manufacturing—Dark goods	10 to 20	100-25
Locker rooms	2 to 5	6-4
Machine shops—Rough work	2 to 5	10-6
—Medium work	5 to 10	15-10
—Fine work	10 to 20	100-25
Offices—Close work		15-10
—No close work		10-8
—Private and general	5 to 10	
—Drafting	10 to 20	25-15

Indications of Wiring Inadequacy

For a number of years illuminating engineers have been encountering installations in which suitable lighting could not be provided because of a lack of capacity in the wiring. This was first evidenced by the blowing of fuses when new lighting equipment was put in operation. It became, therefore, necessary to check up on capacity before placing larger lamps in old installations or recommending suitable lighting even in some new installations. While the advance discovery of the limit saved some embarrassment, it did not produce a happy situation to be unable to provide the illumination needed and desired by the building's occupants.

Even where the safe carrying capacity of the wiring was not exceeded, excessive losses of electrical pressure in the wiring were frequently encountered so that the voltage delivered to lamps was considerably less than it should have been. Such losses were greatest at times when the demand was greatest, and resulted in serious reduction in light output and lamp efficiency. To the user it showed itself in inadequate illumination, a yellowing of the light, and when other loads were switched on and off, a flickering of the lighting. Table II shows a few of the instances of excessive voltage drops found in a brief survey made in 1931 by an electric utility company in Ohio. It is believed that these data are typical and would represent conditions which exist in other communities. Illuminating engineers occasionally report contact with installations where lamps are operating 10 per cent or more below rated volts. Since this means, with tungsten filament lamps, a light output of only about 70 per cent of normal (see curve, Fig. 1), it is easy to understand how unsatisfactory the illumination would be.[2] Oftentimes such conditions have been misinterpreted as being due to poor regulation of the utility's circuits or to defective lamps and have been a source of complaint from this standpoint. In extreme cases building owners have been compelled to incur the costly outlay of rewiring, but in a much larger number of cases, the expense has appeared prohibitive, and unsatisfactory lighting has been continued.

A review of the papers and reports presented before the American Institute of Electrical Engineers and other engineering associations, shows careful treatment of practically every other phase of electrical engineering. Building wiring alone seems to have been neglected, perhaps because it has been considered as an economic

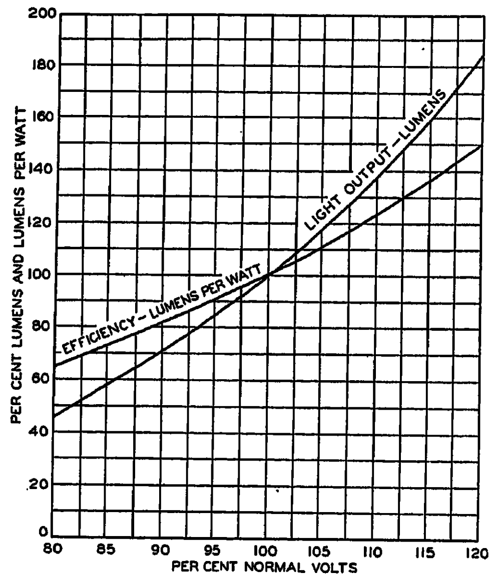

Fig. 1

problem rather than an engineering problem. Inasmuch as the engineering result of the entire system is in so large a measure vitiated by wiring inadequacy, it seems important that more attention be given to this subject.

TABLE II—REPRESENTATIVE EXAMPLES OF INTERIOR WIRING SHOWING EXCESSIVE VOLTAGE DROP

	Sq. ft. area per floor	Volts drop meter to socket	Location
Department store	6,000	0.6	Second floor rear
		5.2	Second floor front
Electric shop	3,000	4.9	First floor rear
		1.3	First floor front
Furniture store	3,500	6.7	First floor
		10.2	First floor front
Jewelry store	3,500	1.8	First floor rear
		7.0	First floor front
Garage	11,000	9.4	First floor rear
		7.6	First floor front
Variety store	4,200	1.5	First floor rear
		5.3	First floor front
Grocery store	3,800	10.9	First floor front
Department store	10,000	4.0	First floor center
		4.0	First floor front
		6.2	Second floor

Moreover, it is not sufficient to provide merely for initial requirements. The wiring should be planned with reference to the expected life of the building anticipating future needs as far as possible. Hence it is also important to consider the trends of lighting practise.

Future Lighting

As already pointed out, the present indications are that illumination levels and degrees of light diffusion will continue to advance for a considerable period. There is no indication of retardation in this respect in the near future.

On the other hand there is a number of more or less new lighting applications going into use which bid fair to increase the electrical consumption. Among these may be mentioned the increasing use of light ornaments, that is, light sources to look at rather than for general illumination, ornamental portable lamps, indoor signal indicators, signs, etc. Some of these ornamental light effects, while originating in the home, club or hotel, are spreading to stores, offices and other interiors.

For the past five years, the practise initiated in Europe of using so-called "built-in" lighting, has been spreading rapidly in this country. Such lighting appeared first in lobbies, corridors, and other public spaces of fine buildings, then in the more elaborate stores, but later in less pretentious places. Since such lighting formerly required special construction in the walls and ceilings, it was applicable only to new buildings or those in which extensive reconstruction was being undertaken. It did not at first appear to apply to buildings planned for the older forms of luminaires. However, modified forms of luminaires similar to built-in equipment are beginning to appear, which can be installed without difficulty in finished rooms and supplied from the usual electric outlets. It is, therefore, quite possible and fairly probable that this style of lighting will extend to buildings not especially planned for built-in lighting. This class of lighting is extending because of its artistic merit and in spite of a considerable reduction in efficiency—measured in lumens per watt. It, therefore, represents an increase in electrical consumption which should receive proper consideration.

Another phase of lighting, which is still in the experimental stage, but receiving enough attention to preclude ignoring it, is the so-called "dual purpose" health lighting. In addition to the visible light, these lamps supply the ultraviolet radiation which is depleted from daylight by window glass and city smoke and which is absent from the light of ordinary illuminants. Such equipment does not inherently require more electricity per unit of light than ordinary lighting, but the installations so far made indicate a tendency to employ higher wattage. It is too early to evaluate even roughly the possible effect upon electrical consumption in buildings. It is, however, mentioned as one of the possibilities bearing upon the situation, which may well receive some consideration, especially where large numbers of people are likely to be excluded from normal enjoyment of sunshine.

All of the items mentioned suggest possibilities of increased demand for light and electric power. A compensating factor would be the use of more efficient light sources. The rapid increase in efficiency of incandescent lamps from say 1912 to 1922 just about kept pace with the demand for more light, so that the electrical demand for a given area and purpose held fairly constant throughout that period. Since then the advance in efficiency has slowed down as the art of lamp making approached the perfection possible with present scientific knowledge. As a matter of fact, it seems to be the conclusion of the best scientific investigators that the incandescent lamp and other solid radiators of light do not offer much promise of large increase in efficiency. It is, however, hardly conceivable that we have reached the limit of light generating efficiency. More efficient electric illuminants are hoped for and expected. Illuminants of considerably higher efficiency have been produced in laboratories. So far all of these have one or another objectionable characteristic so that those familar with the developments of the world's leading laboratories,[3] report that no development is yet indicated as having sufficient merit, including practical features—to warrant prophesying the replacement of the best existing forms of illuminants for general lighting of interiors. Since time is required to adapt and apply new forms of illuminants, it appears unsafe to depend upon any great increase in efficiency being widely applicable to today's installations within the next four or five years.

Other Load on Lighting Circuits

So far, consideration has been given only to lighting applications. Within the past ten years large numbers of small motor and heating appliances have been connected to lighting circuits. These devices include motor fans, bookkeeping and calculating machines, refrigerating equipment, dental, medical and other professional machinery, signals, bell ringers, etc. Such devices are becoming an appreciable part of the load on the lighting circuits, and apparently the next few years will witness considerable increase in the load due to their more extended use. They are valuable services and must be planned for both their own value and for the limits they would otherwise present to good lighting practise.

The Quantitative Element of Wiring

Interior wiring has received a great deal of attention on the part of code writers, and has been the subject of numerous rules. By many in the electrical industry the National Electric Code has been taken as a standard of good engineering, overlooking the fact that the purpose of The Code is fire prevention and other safety features. Being mandatory in character, the code cannot prescribe wiring on the basis of best economic engineering. Because of the common failure of those responsible for

such wiring to provide for later additions to the load on a wiring installation it has been necessary for The Code to anticipate these additions, but still on the basis of safety only. The Code has been the subject of considerable controversy among the various interests involved. Since good engineering would incorporate both the requirements for safety and economic operations, there is good reason to believe that these misunderstandings would disappear and The Code assume its rightful position if good engineering were to prevail in this field.

Early wiring was liberal because of lack of definite knowledge with which to anticipate future demands. More recently, under economic pressure, the latitude has shrunk so that the capacity is often inadequate for the initial lighting. Wiring for a new building is frequently planned and installed before details of the use of different rooms, and therefore, their lighting, are determined. In the absence of generally accepted standards other than the Wiring Code, it has become a widespread practise for designers to establish arbitrary rules and constants of their own making. In the smaller installations, the details of wiring are often determined by competing contractors eager to underbid each other. Where consulting engineers are retained, they are often urged to justify their employment by minimizing investment and so find it difficult to apply best engineering judgment. These varying circumstances all militate against the proper response of wiring practise to the needs of lighting.

To determine investment relations, a committee of illuminating engineers recently made a study of wiring estimates. This committee submitted architectural plans for one floor (9,600 sq. ft.) of a typical building to electrical contractors in several cities throughout the United States. The contractors were asked to prepare bids covering the electrical installation work and material under various specified conditions as to sizes of lamps employed. Eleven different cost estimates were received from the analysis of which conclusions such as the following were drawn:[4] (1) That to cut down the wiring specifications in order to reduce the initial investment was false economy as the greater losses would within a period of a year or two entirely offset the difference in investment. (2) That the investment in the wiring system did not increase in direct proportion to the increase in wiring capacity; doubling the wattage capacity increased the investment only about 1/3 while 50 per cent extra capacity meant an additional investment of only 15 to 18 per cent.

It would appear, therefore, that in the interest of good economic engineering what is needed is a reasonable standard, based upon good lighting practise, with an allowance for advances in the art and probably changes in the use of buildings. Such a standard would do much to overcome the insidious whittling which, in a considerable degree, has been responsible for the unsatisfactory condition.

Adequacy Specification

A few illumination engineers, with country-wide contacts, became conscious of building wiring as a limitation of good lighting about 1924. Previous to this time these engineers had concentrated their attention on lighting practise, namely, the selection of lamps, luminaires and locations. It became obviously important to give attention to wiring if the advance of illuminating engineering were not to be seriously impeded. After several years of study, investigation and consultation with an ever enlarging circle of engineers, a plan was formed, and in the summer of 1928 the National Electric Light Association was asked to promote a movement for better wiring practise. It is not within the scope of this paper to discuss the educational undertaking which resulted.[5] However, it is pertinent to call attention to the specifications, prepared by illuminating engineers widely checked by other groups, and issued under the auspices of the Association.

Preliminary specification paragraphs were agreed upon in the spring of 1929. Immediately some of the illuminating engineers, especially those associated with electric utility companies began an informal application of the standards so embodied. The results were very gratifying. After a year's experience an extension of these paragraphs for commercial buildings[6] was published by the National Electric Light Association. In the summer of 1931, a corresponding specification for industrial buildings[7] was issued under the same auspices.

Several interested groups individually undertook the preparation of corresponding specifications for residence wiring.[8] In the fall of 1931 an industry committee was organized to coordinate the several undertakings into a single standard specification. This work is not yet completed, although the reports indicate that the end is in sight.

The specifications for commercial and industrial structures are undoubtedly the best available expression of the needs felt by illuminating engineers for building wiring. While especially intended for the smaller installations the quantities and principles are applicable to larger buildings. They have been used as a guide in hundreds and probably thousands of installations and all reports seem to indicate that they represent reasonable and proper standards. They are not presented here as final specifications and it is presumed that they will, ere long, require revision to embody later experience and practise as well as more ready acceptance of the need of adequacy.

Conclusion

It is to be hoped that consulting engineers will familiarize themselves with these specifications, subject them to criticism and that out of this there may come generally accepted standards of wiring practise. This would strengthen the weak link in the system of electric lighting, and encourage a normal development along the

lines of good economic engineering. The public could then look with confidence to its advisors in the field of electric lighting, and be assured that good illumination, according to its needs, can be had in any building constructed under responsible auspices.

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Discussion

Philip Sporn: I do not believe that the engineering profession as a whole has recognized the importance to the electrical industry of the most important subject covered by Messrs. Stickney and Sturrock.

For some reason, unexplainable to me at least, the subject of wiring has been looked down upon as one belonging to the low-brow section of the profession and as one not fit for the application of thinking on the part of the engineers. Certainly it has received not a small fraction of the attention given, say, to heavy electrical apparatus or to high-tension transmission, or to underground distribution, or to any one of a dozen fields of application of electricity. And yet, adequate wiring is important in, and is back of, all these fields of application; and in many cases lack of adequate wiring is responsible for the lack of progress in many other branches of the whole industry.

Perhaps the basic reason for this is a general unfamiliarity with the National Electric Code and the status that that code has legally. For some reason there has permeated a general belief that the code as such has legal status, and that being the equivalent to law, there obviously is nothing that engineers can do about it except comply with it. As a matter of fact, the code has no legal status of any kind except such status as is given to it by municipal or other ordinances. On the other hand, a municipality is entirely free to legislate the terms and conditions under which wiring installations will be made within the legal boundaries of that municipality and such legislation may call for installations in direct contradiction to the code. Such cases have actually happened, and of course all those doing business within those municipalities have to comply with the municipal ordinance regardless of the fact that the code may say otherwise.

There is no question, of course, that a national code is a highly desirable thing, but it is only desirable as long as it does not result in throttling the very thing it is intended to promote. What is needed is a code that will recommend the minimum requirements consistent with safety to property and life and will permit therefore, maximum expansion of electrical service with its attendant benefits to the largest possible number of people. The code, too, ought to be flexible and ought to march hand in hand with technological progress and permit the easy change and experimentation leading toward change when technological progress indicates its safety and desirability. There is no reason to doubt that when a larger percentage of the Institute membership than is doing so at the present time begins to take an active interest in the code, we will get such a set of rules. When we do, we will certainly have gone a long way toward making possible economical wiring, and therefore, will have taken a great step toward providing adequate wiring, the need of which in one branch of the industry, the illumination branch, has been so adequately presented by Messrs. Stickney and Sturrock.

To indicate the effect that the application of well-known engineering principles to wiring can have on the cost of such work, and what it can do toward providing adequate wiring without materially increasing the cost, it might be interesting to cite the development of the bare neutral conductor method of wiring. Bare neutral conductors are at present approved by the code for service entrances only but even in that case are restricted to the use of bare neutral conductors in metallic rigid conduit, the code does not permit bare neutral conductors in armored cable construction. The latter construction is, however, fully approved by many municipalities and their accredited inspection agencies for use not only in services but in interior wiring as well. It used to cost \$18.50 for labor and material to install a 30-ampere service, using a 30-ampere service switch and ¾-inch conduit with two No. 8 conductors (Code approved methods) and we found that to employ the same methods of wiring, using a 1-inch conduit and three No. 6 conductors, the lowest cost possible was \$28.00; this, too, after a great deal of trimming and compromising in methods and materials, but still keeping the whole within the minimum code requirements. On the other hand, by going to bare neutral armored cable construction we were able to reduce this cost to \$21.50, a reduction of over 23 per cent against the standard method, and an increase of only a little over 16 per cent over the standard 30-ampere, two-wire service. For this increase, however, the capacity of the service and its ability to permit electrical development in any home fed through the service is increased 230 per cent; that is, it brings up the possible electrical development within that home from 3.4 kw to 11.5 kw.

Morgan Brooks: The paper by Messrs. Stickney and Sturrock is a timely and impressive appeal for vision in planning building wiring to meet the possible illumination demands of the future. With decreasing costs of the materials for wiring this appeal should bear immediate fruit.

The authors state that improvement in illumination efficiency seems to be approaching a limit, but do not stress the present tendency of public service companies to reduce electricity rates as a spur to further rapid increase of lamps and appliances. With the predicted installation of air-conditioning apparatus in our homes just what wiring will prove adequate is a debatable question.

A field of considerable importance to the house owner is revision of inadequate wiring without recourse to complete replacement. The use of vacuum cleaners and of laundry equipment has usually caused no objectionable disturbance of illumination since their use is confined to daylight hours. Where coffee urns, toasters and chafing-dishes affect dining-room illumination adversely a single additional circuit, often inexpensively wired from the basement to convenience outlets for the offending utensils, and purposely connected to the side of the distribution

system opposite that serving the lighting circuit,—will often make the use of such devices a positive illumination advantage by causing an increase of the lighting voltage.

In too many instances the distribution of circuits between the two sides of a three-wire system is determined solely by their direction of approach to the cutout cabinet. Outlets may thus be equally balanced, yet it may happen that nearly all the lamps in use at any given instant are connected on the same side of the system resulting in unnecessary reduction of voltage. Sometimes judicious reconnection of circuits at the cutout cabinet will save the expense of rewiring. The illumination engineer should therefore insist on an intelligent distribution of circuits to maintain current balance under all probable lighting conditions.

F. C. Caldwell: The paper calls attention to the approximate doubling of the demand for illumination during the past decade, but the extension of this trend in both directions may be considered. Forty years ago, following the examples of gas lighting one foot-candle was considered good general illumination where ten or more are called for now. Again, looking toward the future, we see no natural limit to this desire for higher illumination, unless it be daylight with values around one hundred foot candles or even more.

As illustrating the opportunity for real engineering in connection with the wiring of buildings, a simple application of differential calculus shows that the greatest economy of copper will be attained for a two-wire system, when the permitted voltage drop is divided between a feeder and its branches in proportion to the length of the feeder and the average length of the branches. Similar relations can be worked out for three-wire feeders with any given relation of neutral to outside wire. I have never seen this simple principle stated in treatises on wiring.

Too much emphasis cannot be placed on the importance of the specification by the architect of conduit and wire sizes, so that all contractors will bid on the same installation. Too frequently, this important part of the design of the building is passed on to the contractors by the practise of specifying the load and the permitted drop only. Compliance with these values is seldom checked.

J. M. Bryant: This paper is a timely one to give an added impetus to a work which has been started by the leading illuminating engineers of this country during very recent years. It is fitting and necessary for the American Institute of Electrical Engineers to lend its influence towards a change in the existing codes both national and local to assist in the rapid improvement of building wiring systems. One of the greatest steps already made in this direction has been in the education of the architect in providing for adequate building illumination in the design of new structures. What is now needed is to secure the interest of electrical engineers in securing by all legitimate means an increase in the standards for wiring so that the conductors in new structures may have sufficient capacity to permit increasing the illuminating standards of all buildings in line with modern tendencies.

There is probably no field of building illumination which better illustrates the changing tendencies than that of the public school and buildings in institutions of higher education. Before the advent of night school classes and classes in extension it was possible to schedule the work so as to miss the hours when it was thought that illumination was needed in such rooms. However, in modern illumination it is found that many rooms need artificial illumination at any hour of the day to conserve the eyesight as well as to permit more rapid work by the students.

I can best illustrate this by two or three cases. The first is that of a University which had adopted a 220/440-volt three-wire system of distribution derived from a 440-volt two-phase power system. In the design of new buildings farther from the power plant it was necessary to adopt a higher voltage for power distribution and at the same time the more efficient 115-volt incandescent lamp on a 115/230-volt system. This made it desirable to change over the older buildings to the use of the 115-volt lamps to prevent accidents in the use of the wrong lamp. The advent of the mazda lamp at that time saved the day to some extent although it did not permit of increasing the standard of illumination without the use of open wiring in many of the rooms. Another set of buildings illustrating this point was an old school for the blind which was to be adapted for the "Eyes of the Army" during the World War. The only lighting in these buildings was in the living quarters of the Superintendent and the staff. The old wards and classrooms, of course, needed no light for blind pupils. A third set was in a University in which the business manager held the opinion that if we provided adequate illumination in the buildings that the rooms would be used during the evening and the lighting bills of the University would increase. In spite of this opposition, a compromise plan was worked out by providing adequate illumination in some of the buildings and in providing adequate wiring and lamp spacing in all new buildings so that modern tendencies could be followed.

Since the architects of this country are taking such an active interest in adequate illumination as well as in the use of light for decorative purposes, the American Institute of Electrical Engineers should cooperate with standardizing bodies in the adoption of new codes of wiring. It should also do all in its power to see that there is a proper consideration given to the illumination and wiring of all buildings which are constructed in such a manner that it is extremely difficult as well as costly to make changes in the wiring and distribution equipment after the building has been put in use. In this line public school buildings should receive especial attention.

L. W. W. Morrow: There are three aspects of wiring and lighting that should receive serious consideration by every man in the industry. These are humanitarian, business, and technical. Man is a seeing machine and the new conception of lighting is to add to lighting for efficiency more light for the humanitarian effects we desire. Our ideas of illumination are so far ahead of practise and our social values involved in illumination are so great that industry attention should be focussed on the topic.

Then again, wiring and lighting offer enormous business possibilities to the industry. Few engineers realize that a load of 20 watts per sq. ft. for lighting means that each floor of an office building offers a load of 1,200 kw. and thus a 30-story building offers a load of 36,000 kw. High grade engineering and detailed attention is devoted to a 500-kw. industrial power load yet the lighting load is infinitely larger and receives little attention. Each home market offers from 10 to 15 kw. of load if adequately sold and engineered. Thus from the business point of view adequate wiring for lighting is a major task and requires high grade engineering.

In a strictly engineering sense adequate wiring and lighting deals with equipment and apparatus—some thousands of items. A piecemeal development has occurred and empirical standards exist. Undoubtedly engineering attention could be focussed on this aspect with resultant simplification, standardization and development. By way of contrast, consider the high grade engineering that has been focussed upon the relays and other devices used in telephony and telegraphy. These devices are precise and reliable to an advanced degree and carry voltage and current ratings very frequently comparable to those found in wiring for light and power. But consider the relative size, weight and amount of material used for devices in the two fields. Undoubtedly engineering attention to equipment used in wiring will pay enormous dividends.

All engineers should be interested in this subject and it is incorrect to consider the engineering of wiring and wiring devices too "low brow" for serious attention. No more fruitful field for engineering exists in the industry and it should have serious attention.

Taylor Reed: A revised code on adequate wiring of buildings should set limits of permissible momentary dip of voltage. A case in point would be to fix adequate residence wiring to preclude excessive momentary dip of voltage and consequent violent flicker of lights due to the starting of refrigerator motors.

P. L. Alger: This paper has presented very clearly the need for more liberal wiring systems to improve lamp efficiencies and reduce the power consumed in I^2R losses, as well as to anticipate future requirements.

It appears to me that any standard wiring code can properly only call for the minimum requirements consistent with safety, and that the provision of facilities in excess of the minimum must be left optional with the builder. However, if builders generally appreciated the direct savings in power bills obtainable by improved wiring, and especially if these figures were generally available in some authoritative form, I feel sure that more liberal wiring systems would generally be called for.

I, therefore, suggest that the wiring code committee prepare a supplement to the standard code, which would explain the minimum character of the standard code provisions, and give detailed figures on the possible savings to be made by the use of larger wire sizes and more numerous outlets. In particular, this pamphlet should give tables of the annual costs of the power consumed in resistance drop in the wiring for various wire sizes under typical load conditions for various assumed power rates. Also, the costs of the power losses due to poorer lamp efficiencies at low voltages should be tabulated. Besides these definite figures, estimates of the excess cost for additional wiring done after building is completed over the cost of installation during construction should be cited. Such a pamphlet, giving a convenient means for the layman to calculate the economic benefits of installing improved wiring systems should be very helpful in the promotion of more liberal installations; and, if attached as a supplement to every copy of the wiring code, it should prove a most effective means of advancing the objects which Messrs. Stickney and Sturrock so effectively advocate.

E. B. Murray: I wish to express my approval of this paper. There is one point, however, that I wish to criticize. The paper does not insist strongly enough that the architect or engineer connected with the designing of a building should take into consideration the importance and necessity of installing adequate copper in the circuits, and that if they fail to do so, they are not giving the best service to their clients.

I have had the honor of being retained in a consulting capacity on numerous large office buildings throughout the United States and I have yet to find an electrical contractor on an undertaking of this nature who has not called attention to the savings which he can make in the electrical setup by the reduction in circuit size.

Where every economy was necessary, I have insisted that at least oversize conduits be installed to facilitate the pulling of large wires when it became necessary.

Speaking from the standpoint of the building operator, statistics indicate that there is a very marked increase in the demand of tenants for higher lumen output at desk level. It is impossible for a building manager or operator constantly to check lamp sizes in a tenant's space for quite frequently the tenant will purchase and install at his own expense larger lamps without the knowledge of any of the building employees. In addition to that, we find that tenants are constantly adopting electrically operated office equipment which is naturally connected to the lighting circuit.

It is apparent, therefore, without any suspicion of what is going on, the building operators quite frequently find themselves confronted with a succession of blown fuses, which an investigation discloses is due to no other reason than an overloaded circuit.

Unless ample provisions are made on the plans for an increase of copper at not less than 50 per cent of the anticipated load, it is impossible to meet the increasing demands later on due to the fact that the conduit sizes are fixed and cannot be changed.

Careful determining of the wattage requirements per square foot of rentable area is one of the most important computations which should be made at the outset. The size of the circuits thus determined should then be increased arbitrarily at least 50 per cent.

Andrew Steers: After reading the paper with a great deal of interest, I endorse the reasoning and conclusions that it sets forth.

One of the weaknesses in modern business-building design and construction which has resulted in loss of operating efficiency and increased expense, has been the inadequacy of both power and lighting wiring. I believe it will not be difficult to get experienced business property owners and managers to make more adequate provision in this respect in all types of buildings they will build in the future.

The very great increase in the use of electrical appliances in the offices of today, coupled with the constant changes in the field of illumination, demand that all interested in this phase of building operations give serious consideration to the provision of sufficient conductors to meet modern conditions and provide for substantial load increases during the future life of the property.

My suggestion is that these studies be continued and that data, as it is prepared, be distributed to the leading architectural concerns and owners of business properties.

C. H. Roe: This paper serves a very important purpose in inviting further attention to the relation of adequate wiring and good illumination, a subject which is very apt to receive less attention than it deserves because of our present-day economic situation. The subject is so broad that obviously the authors can do no more than treat it in very general terms.

The paper recognizes the scope of the subject as including buildings of all types. It would seem, however, that residence wiring should be recognized as being of special importance in this connection because of the prominence of the residence load in the future business estimates of the various components of the electrical industry.

All that the paper says about tendencies to cut expenditures for wiring, on the part of consulting engineers, architects and wiring contractors, applies with particular force to residential work. Because of the greater prevalence of such practises in residence wiring, it follows that in this field lies that much greater opportunity for improvement in wiring adequacy.

Adequacy of residence wiring has at least two principal components; the first is adequacy of copper as measured by gage size of conductors. In most residences this is of less importance since limits of the actual physical carrying capacities of wiring most commonly used in residences have not yet been approached. Of considerably greater importance is the footage of wires and the provision of numerous outlets. In most homes greater convenience and greater current consumption would follow the installation of a few more feet of No. 14 wire than would result from the expenditure of the same amount of money in providing larger conductors in a smaller installation. Too many appliances are still used through lamp sockets. In fact the expression "lamp-socket appliances" is still frequenctly used in the industry. As for illumination, with which the paper is chiefly concerned, it is only necessary to visualize the all too common handling of flexible cords in living room, library and bedroom, in order to permit the use of the number of table, floor and bridge lamps which the modern home has come to regard as essential. A few baseboard outlets for the connection of portable lamps would seem to be of far greater importance than calculations of lamp sizes and carrying capacity of wires.

When considering adequacy of outlets for lighting purposes, one should not overlook the desirability of adequate switching facilities. Three- and four-point switches are conveniences to infrequently found in the modern home. Switch control of base-

board outlets adds considerably to the convenience of the householder. One of the best protective devices in the world is the master switch in the bedroom for switching on lights throughout the house. All of these things have to do with adequacy of control of lighting rather than with the provision of adequate illumination through consideration of lamps or copper sizes.

It is not proposed that the phases of this subject presented above are of any greater importance than several other aspects of the general question. It is only suggested that they should be given suitable attention in connection with any study of the subject.

Walter Sturrock: From the tone of the discussion the authors of this paper feel very much encouraged. I don't think there is a single thought expressed which is in any way contradictory to the authors' analysis of the problem.

Several of the discussors referred to the National Electric Code and in order that there will be no misunderstanding I would like to emphasize that the National Electric Light Association Minimum Specification for Adequate Wiring not only meets the requirements of this safety code but recommends heavier conductors in so far as they are justified from the standpoint of their being economically practical. The Minimum Specification does not discuss materials to use or methods to employ as such questions enter into an entirely different phase of the problem which was considered as being beyond the scope of the work carried on by those preparing the specification. It might also be mentioned that the Minimum Specification for Adequate Wiring as referred to was designed primarily for smaller buildings where a competent engineer's advice is not usually secured. It is applicable to larger buildings and will be found helpful to consulting engineers who may be employed on the job. Copies of the specifications are available through the headquarters of the association as indicated in the bibliography.

One of the discussors commented on the fact that few consulting engineers give serious thought to the wiring of lighting circuits, because there are more complicated problems in the distribution of power which have capitalized their time. As mentioned by him, this condition should not exist because proper lighting is an essential for every interior and its design demands serious consideration all the way back to the utility company's generator.

In stores, offices and other commercial buildings the relative importance of light and power circuits is no doubt readily recognized, but in industrial plants it is not so evident. A recent survey in 20 typical industrial plants in Detroit revealed the fact that approximately one-third the total connected load was lighting and two-thirds power. In this particular city, engineers have given a great deal of valuable advice on lighting with resulting satisfaction to all concerned. In contrast with the Detroit survey, light and power ratios were obtained from typical plants in an industrial section of Ohio where very little or no engineering work had been done on the design of lighting circuits. This latter survey indicated only 13 per cent of the total connected load as being used on the lighting circuit.. These Ohio industrial plants were all inadequately lighted and presumably were so inadequately wired that up to date lighting could not be obtained without major changes. It cannot therefore be overemphasized that engineering advice on lighting circuits wherever they may be found is unquestionably worthwhile. And this advice, when put into practise, will assure the owner that he will not only have adequate wiring capacity to meet the demands for the initial connected load but also to permit a reasonable increase in load which may be expected during the next few years to come.

G. H. Stickney: After reviewing the discussion, we are highly gratified by the splendid response which emphasizes the importance of wiring to the progress of electrical engineering works. Practically the only criticisms are with reference to omissions or lack of stress on certain applications. This was intentional as we considered it best to concentrate our treatment on those aspects which came within our intimate experience, and concerning which we could speak from first hand knowledge.

The discussion has realized our hope that others would emphasize other phases of major importance out of their own viewpoints. As we have mentioned in the paper, the problems extend beyond the lighting field, and any solutions must give proper weight to these other applications.

The relation of the National Electric Code came in for considerable attention, and considerable diversity of opinion is reflected. It is not necessary to repeat our own views expressed in the paper. Obviously it is desirable to carry this question further towards unanimity of opinion as to what is right and best.

The paper, strengthened by the discussion, is merely a start in calling engineering attention to problems of wiring which needed more study, investigation, and coordination.

It is our hope that a suitable technical committee will take hold of the subject and provide a sound engineering basis, on which useful advances of the art can be assured. We believe that the unbiased interest of the A.I.E.E. can provide the kind of leadership under which the wiring of buildings can be developed to serve its proper part in the electric systems of the country.

Induction Motor Versatility

Nature of Its Applications

BY E. W. HENDERSON[1]

Member, A.I.E.E.

THE polyphase induction motor was first announced by Tesla in 1888. It is thus some forty-four years old. It demanded, for its operation, a polyphase system of power distribution. Prior to its inception, alternators and systems were single-phase, frequencies high (120 to 133 cycles), and distribution systems limited in many respects.[2] The induction motor ushered in a new era of electrical development which has grown and expanded to be the giant as we now know it.

Today, the induction motor bids fair to bring about another revolution of ideas as regards its use and capabilities. Heretofore, particularly in respect to the squirrel-cage motor, it has been confined to rather restricted fields of application. Its starting characteristics and the need of special starting devices were against it. Now limited-starting-current motors such as those employing double cage rotors are overcoming these starting objections. The use of these across-the-line motors has encouraged the idea of throwing standard motors directly on the line, and has encouraged also the use of induction motors for applications demanding frequent starting or reversing. Formerly, the squirrel-cage motor was looked upon as one to be applied only for constant speed service. Today, there are many applications where the operating range covers wide variations in speed.

There are many new applications which would have been considered impossible a few years ago. We look at things today from a different angle and new conditions demand a change in some of our former opinions. The purpose of this paper is to point out that the induction motor is becoming something of a universal motor, not from the standpoint of the number of motors used or the widespread territory over which these motors are used, but from the standpoint that it is today being applied to operations which are extremely diversified in type.

The demand for adjustable speed has been met, to some extent by the slip-ring motor. The objections to this type of motor are chiefly that the speed is not independent of the load and that the speed reduction is obtained at the expense of efficiency. The commutator type of motor with variable brush spacing is essentially a slip-ring motor with an opposing e.m.f. substituted for a rotor external resistance and offsets, in some degree, these disadvantages of the slip-ring motor. The multi-speed squirrel-cage motor is more simple in construction and offers several fixed speeds. It cannot give adjustable speeds in the strict meaning of the word, and yet it is being more widely applied than formerly, and is finding new applications on machine tools and special drives, lifts, planers, etc.

There is a number of applications of single winding, simple squirrel-cage motors which cover a great variety of uses and it is these which it is desired to mention particularly. Probably the best way to classify these applications is from the standpoint of slip and torque, and Fig. 1 is shown to indicate the divisions which can conveniently be made for this purpose. Under division I are indicated applications covering slips of approximately 0 to 20 per cent. Division II covers a wide speed range of slips from 20 to 70 per cent. Division III covers the balance of the speed range, *viz.*, from 70

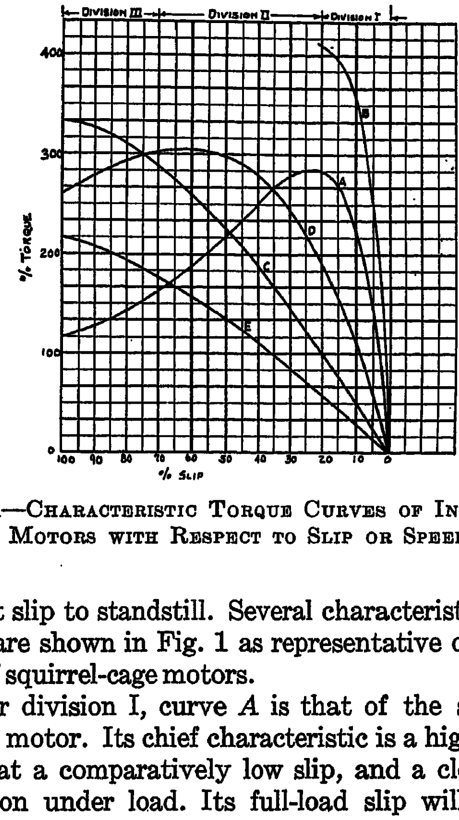

FIG. 1—CHARACTERISTIC TORQUE CURVES OF INDUCTION MOTORS WITH RESPECT TO SLIP OR SPEED

per cent slip to standstill. Several characteristic torque curves are shown in Fig. 1 as representative of various types of squirrel-cage motors.

Under division I, curve *A* is that of the standard, low-slip motor. Its chief characteristic is a high pullout torque at a comparatively low slip, and a close speed regulation under load. Its full-load slip will average about 3 per cent. Its applications are so well known that no details are given here.

There are some special applications which demand less slip than 3 per cent, or which require a torque characteristic such that there will be a large increase in torque for a small drop in speed. In the former class belong loom motors as universally used in the textile industry. In the latter class are special centrifugal machines such as babbit pots where the load comes on the

1. Reliance Electric & Engineering Co., Cleveland, Ohio.

2. *Elec. Journal*, Vol. I, page 558.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

motor after it is up to speed. The large inertia load demands a rapidly increasing torque as the speed drops, else the drop in speed will be excessive and valuable production time lost in getting the machine back up to full speed. Certain tapping machines demand this same characteristic for the same reason. Curve *B* of Fig. 1 indicates the type of speed-torque curve covering these applications.

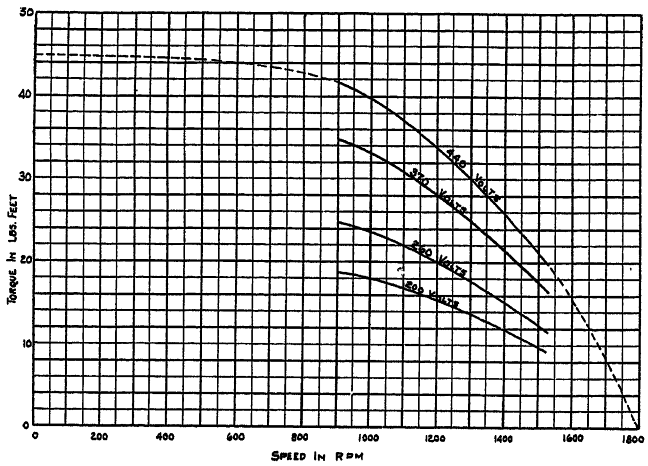

Fig. 2—Set of Speed-Torque Curves of an Induction Motor Used on an Automatic Tension Device. Torque Increased with Slip

Curve *C* indicates the torque curve of a squirrel-cage motor with a comparatively high-resistance rotor. Such a motor is used where high starting-torque is desirable and where the excessive slip is no disadvantage to the work in hand. Applications cover motors for hoists, cranes, elevators, conveyers, skips, etc. On the other hand, this excessive slip may be the thing which is highly desirable. Applications of motors to slow-operating presses, shears, drop hammers, etc., where these tools are equipped with flywheels, demand that the speed drop be sufficient to allow the flywheel to restore part of its kinetically stored energy to the tool drive and thus relieve the motor. This practise allows the use of a low-horsepower-rated motor and makes for a constant power demand.

Curve *D* indicates the torque curve of a motor with a rotor resistance between that of *A* and *C*. It has a slip at full load of approximately 8 per cent and is the motor used for average punch-press service, as its high torque and slip adapt it for this work. It is used extensively for motors which have to start or reverse often, such as tapping machines, threaders, and many special applications.

Division II of Fig. 1 covers slips of 20 to 70 per cent. This range is generally thought of as belonging entirely to the slip-ring motor, yet squirrel-cage motors are used within this range also. One interesting application is that of automatic torque control. For example, in the wire drawing industry it is an advantage to keep a constant tension on the wire as it is reeled. If this is done, then as the reel builds up, the torque of the reel motor must increase due to the increasing radius at which this constant wire tension is to be maintained. Fig. 2 indicates a set of torque curves of a motor used for such a purpose. The automatic rise in torque with decrease in speed fits the motor perfectly for such applications. Only one full torque curve is shown in Fig. 2. The working portion of the lower torque curves are obtained by varying the voltage on the motor by means of a simple auto transformer. Evidently the motor can be designed to give practically any torque variation required.

There has also been a demand for tension control in which the motor torque increases as the speed increases. Such a set of torque curves is indicated in Fig. 3 where again the motor may be designed to meet the conditions required. The decreasing torque of the spooler motor, as the spool fills up in this case, provides constant tension on the wire but the increased torque corresponding to this constant tension is more than offset by the decreased friction and windage of the spool, so that the total desired torque falls off with the speed. If the speeds run to a high slip or cover a wide range, very special motors may be necessary. The motor copper losses vary with the slip and special ventilating schemes may be necessary, or recourse may be had to the slip-ring motor. Since the maximum torque point can be moved about at will, any desired slope of torque curves can be had with close approximation to a straight line over the operating range.

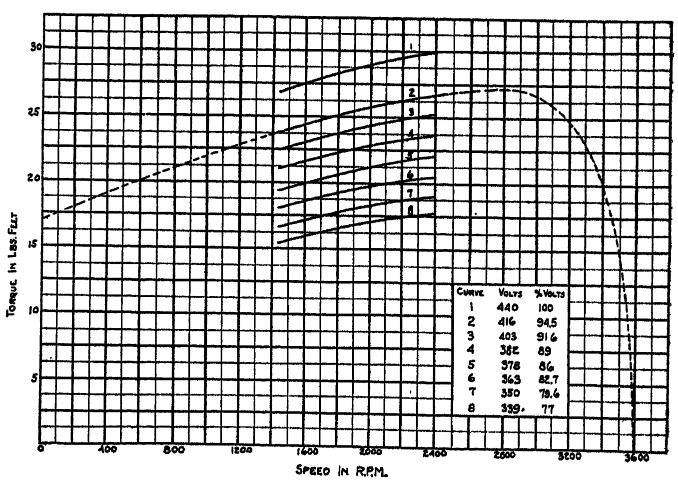

Fig. 3—Speed-Torque Curves of Induction Motor Used for Automatic Tension Control. Torque Decreases with Slip

Division III, covering slips of 70 to 100 per cent, covers applications of induction motors where the motor makes only a few revolutions or crawls at a low speed. Such applications cover valves, screw-downs, certain door-lifts such as for steel mill furnaces or hoppers, special stalled torque-motors for various types of control, etc. The value of the starting or low-speed torque will depend on the type of motor used, with respect to

the torque at higher speeds, as indicated in the curves of Fig. 1. The starting torque can be made to vary over wide limits by adjusting the rotor resistance. Some applications will demand a high starting torque, others a low starting torque. Of particular interest in the latter type are motors of especially low starting and reversing torque as used for laundry machines. Such motors have an inherent high reactance. There are other special applications where too quick a start may result in damage to the product and which demand low starting torque, and of the opposite type are special high-torque, short-time ratings for such applications as theater-lifts, tool shifts, etc., which require abnormally high starting torques.

Division III might be extended to include stopping as well as starting characteristics. The stopping of squirrel-cage motors by means of direct current offers some interesting considerations. Figs. 4 and 5 show tests on a

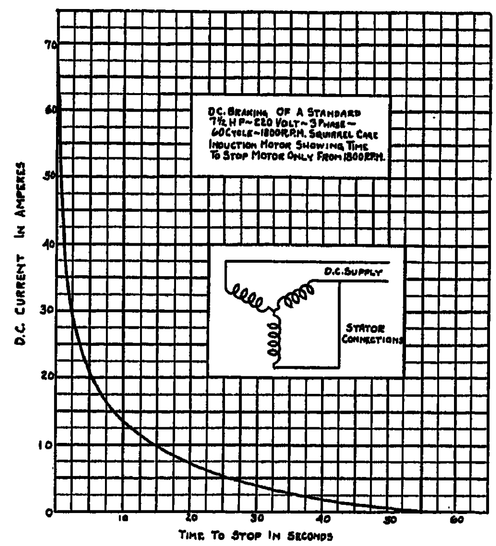

FIG. 4—D-C. BRAKING CHARACTERISTIC OF A SQUIRREL-CAGE INDUCTION MOTOR, SHOWING TIME TO BRING MOTOR TO STOP

standard 7½-hp., 60-cycle motor stopped by applying direct current to the stator. Since it would take an infinitely large current to stop a motor in zero time, the curve of Fig. 4 is asymptotic to the vertical axis. It is not asymptotic to the horizontal axis due to the action of bearing-friction. As the rotor slows down, the secondary frequency changes from that of line frequency less slip frequency, to zero frequency, so that conditions are somewhat similar to those when starting from standstill and running up to speed, where the rotor frequency changes from that of the line to slip frequency.

The braking effort for a given value of direct current will depend on the manner in which the terminals are connected to the d-c. supply. For a Y-connected stator and connection as shown in Figs. 4 and 5, the d-c. ampere-turns per pole[3] = M_1 such that

$$M_1 = \frac{N}{3} I_1 + 2\left(\frac{N}{3} \times \frac{I_1}{2} \times \cos 60°\right) = 0.5\, N I_1 \qquad (1)$$

Where only two terminals are used, the ampere-turns per pole are

$$M_2 = 2\left(\frac{N}{3} I_2 \cos 30°\right) = 0.578\, N I_2 \qquad (2)$$

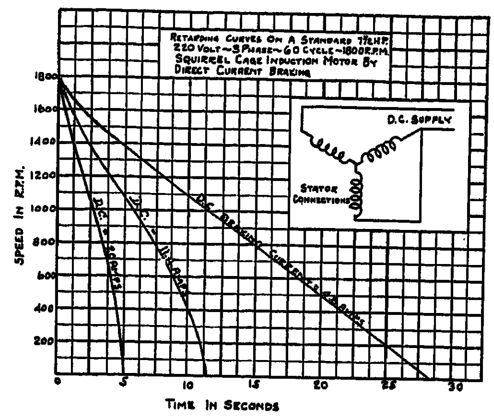

FIG. 5—RETARDATION CURVES OF A SQUIRREL-CAGE INDUCTION MOTOR WHEN STOPPED BY DIRECT CURRENT

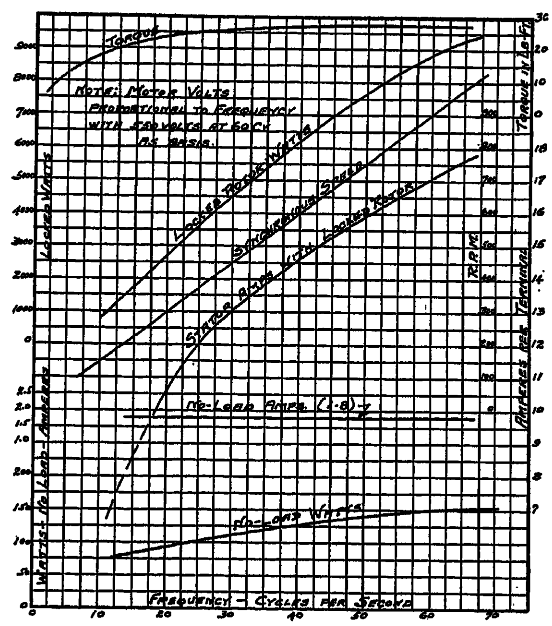

FIG. 6—TEST DATA ON A SQUIRREL-CAGE MOTOR WITH A WIDE SPEED RANGE BY VARIABLE FREQUENCY CONTROL

Three-phase, 16.7/36.7 cycles, 153/336 volts, 241/532 r.p.m.

For a delta-connected stator and two terminals connected to a common d-c. line, the third being connected to the other d-c. line, the ampere-turns per pole are

$$M_3 = 2 \frac{N_0}{3} \frac{I_3}{2} \cos 30° = 0.289\, N_0 I_3 \qquad (3)$$

3. See *Measurement of Stray Load Loss in Polyphase Induction Motors*, C. J. Koch, A.I.E.E. TRANS., Sept. 1932, p. 756.

For a delta-connected stator using two terminals only, the ampere-turns per pole are

$$M_4 = \frac{N_0}{3} \times \frac{2\,I_4}{3} + 2\frac{N_0}{3} \times \frac{I_4}{3} \cos 60°$$
$$= 0.333\,N_0 I_4 \qquad (4)$$

where N and N_0 represent the turns per pole, and I_1, I_2, I_3, and I_4 represent the total direct current. It will be noted that for equal currents approximately 15.6 per cent more flux will be created by connections ((2) and (4) than for connections (1) and (3). For equal voltages impressed on the different connections, (1) and (3) give the greater braking action. Although the braking ampere-turns depend on the connections as indicated in the above equations, it can readily be shown that equal ampere-turns in each case give equal heating or power consumption.

The a-c. ampere-turns per pole are

$$M_5 = 0.707\,NI \text{ for Y-connected stators} \qquad (5)$$

and

$$M_6' = 0.707\,N_0\frac{I}{3} = 0.408\,N_0 I \text{ for } \Delta$$
$$= \text{connected stators} \qquad (6)$$

where again N and N_0 equal the turns per pole and I represents the effective terminal alternating current. The ratio between d-c. ampere-turns and a-c. ampere-turns is thus apparent.

When a squirrel-cage motor is stopped by a-c. plugging, the alternating current rises anywhere from 5 to 10 times the full-load current of the motor. To stop a squirrel-cage motor by d-c. braking also requires considerably more than the value of rated alternating current, if the stopping is to be done in a reasonable time. The losses, however, are less for d-c. stopping than for a-c. plugging, with the stop accomplished in the same time in each case.

If a squirrel-cage motor is stopped from different speeds by applying a direct voltage proportional to the speed, the stopping time will decrease as the speed increases. For a two-to-one range of speed, experiments indicate that the time to stop from the high speed will be about 75 per cent of the time to stop from the low speed.

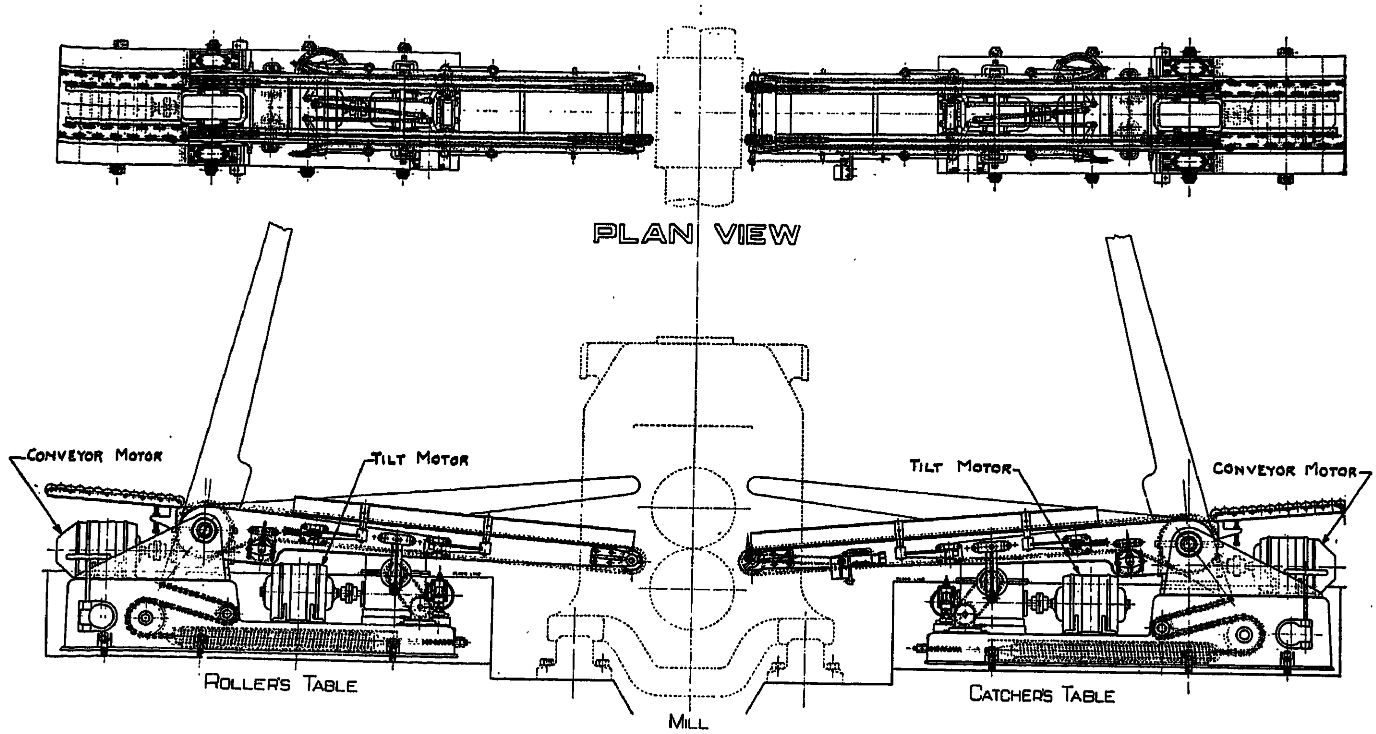

FIG. 7—DETAILS OF MECHANISMS AND MOTOR MOUNTING ON ONE MAKE OF AUTOMATIC TABLES USED IN ROLLING SHEET STEEL OR PLATE

An application of a squirrel-cage motor to cover a wide speed range is that of a gang of such motors driving individual units of a conveyer system where the speed range is obtained by applying variable frequency to the motors. Such cases generally require constant torque characteristics, and by applying a voltage proportional to the frequency, the torque is practically constant over a wide range of speed. Fig. 6 shows the characteristics of a squirrel-cage motor when operated under these conditions.

Squirrel-cage motors have been applied where extremely low speeds are required by running them on frequencies as low as 3 to 5 cycles. When operated on such low frequencies, the characteristics differ immensely from those for standard frequencies. One peculiar fact is that under these conditions the locked

current, no-load current, and running-load current are almost of equal value. The plugging current may actually be less than the running current if the plugging is done at the instant of low voltage.

Applications of squirrel-cage motors for rapid and oft-repeated reversing or starting duty have been exceedingly active in the last few years. First came such motors as applied to tapping machines, drills, and tools of a similar nature. Small planers have been equipped with 10- to 15-hp., squirrel-cage, multi-speed motors reversing as often as fifteen times a minute. Squirrel-cage motors have been used for special machine operations where a reversing duty as high as 30 to 40 reversals a minute has been demanded, in order to eliminate complicated mechanical reversing mechanisms. Quite recently, motors for rapid reversing duty have been demanded for a special application known as catcher tables, one type of which is indicated in Fig. 7. The author presented a paper before the Pittsburgh Section, A.I.&S.E.E., in March, 1932, on this particular application and its allied problems, and it is cited here simply to indicate the increasing tendency in the use of

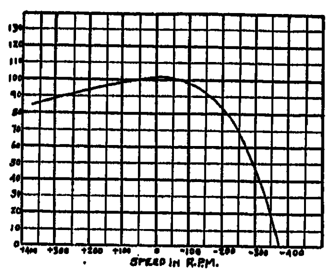

FIG. 8—TORQUE CURVE OF 25-CYCLE—375-R.P.M. REVERSING MOTOR FOR CATCHER-TABLE SERVICE

squirrel-cage motors for reversing duty. Figs. 8, 9 and 10 show characteristic curves of a 25-cycle motor for such service.

A very interesting study of a squirrel-cage motor starting from rest occurs when a crank action is interposed between the motor and the final mechanism, particularly if the crank moves through 180 deg. in completing the movement desired. Where the crank is actuated by a motor, either directly or through some reduction unit, and starts with the crank on dead center, the equivalent reduction ratio between mechanism and motor continually changes from infinity to some minimum value. The acceleration of the motor must be combined with the acceleration of the mechanism, and this changing reduction ratio must be taken into account in the calculation of the total equivalent WR^2 at the motor. This condition, combined with a torque characteristic which changes with speed, leads to a solution of the velocity and acceleration of the mechanism which can be obtained only by the method of assumption and trial. In cases where material is conveyed by such a mechanism in a vertical plane, it is usually essential that the acceleration at no time exceeds that of gravity. The minimum time of such a cycle is thus rather definitely fixed.

Assuming that the mechanism is given harmonic motion, the velocity will follow the law

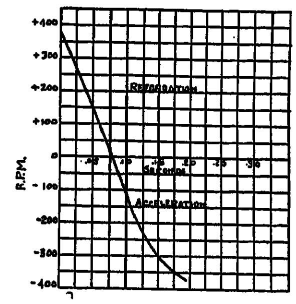

FIG. 9—RETARDATION AND ACCELERATION CURVE OF MOTOR SHOWN IN FIG. 8 USED ON 25-CYCLE SERVICE

$$V = \omega R \sin \omega t$$

Where

ω = angular velocity of crank in radians per second,

R = radius of crank.

With the maximum velocity equal to ωR, the maximum acceleration will be $\omega^2 R$.

For example, assume a total movement of 3 feet. Here $R = 1.5$ (crank to make 180 deg. for total movement).

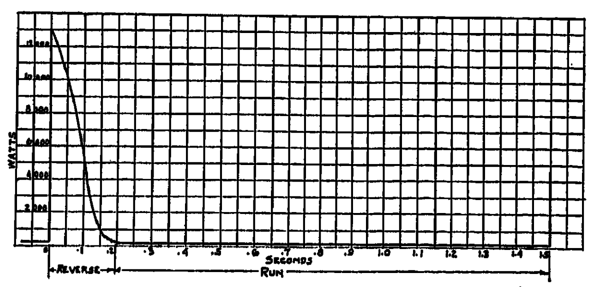

FIG. 10—ENERGY LOSS DURING A CYCLE OF REVERSAL AND RUNNING FOR 25-CYCLE CATCHER TYPE MOTOR OF FIG. 8

$$\omega^2 R = \omega^2 \times 1.5 = 32.2\,(= g)$$
$$\omega^2 = 21.5$$
$$\omega = 4.62 \text{ radians per second.}$$

$$\text{Time to traverse } \pi \text{ radians} = \frac{\pi}{4.62} = 0.68 \text{ seconds.}$$

The time of the movement could thus not be less than 0.68 second on the assumption that the motor ran at constant speed. Since the motor must start from rest,

the minimum time of the cycle will be greater than 0.68 second if gravity is never to be exceeded. Such applications, therefore, demand considerable study both from the builder of the mechanism and the motor application designer.

There are many other special applications of the induction motor which might be mentioned. Enough have been indicated to show the widely diverse type of applications which can successfully be met by this motor. This diversity gives to the motor a certain universality which will make it even more popular in the future than it has been in the past.

Discussion

E. W. Henderson: In the paragraph following equation (6) some general remarks are made on the value of d-c. braking current. Fig. 11 is more specific and shows some interesting details; it also covers test data on a standard two-hp., 1,200-r.p.m. motor. Curve A is the speed-torque curve for the motor between standstill and synchronism *i. e.*, between rotor slips of 1 to 0. Curve C is the speed-torque curve of this same motor with direct current applied to brake it from 1,200 r.p.m. to standstill. Under these conditions the rotor frequencies correspond to slips of 1 to 0. This curve was obtained by using the dynamometer as an adjustable speed motor to drive the two-hp. induction motor under the conditions of a fixed d-c. current in the stator. The resulting torque was read on the dynamometer. The conditions in the rotor as regards frequency are identical in curves A and C but the shape of the torque curves are quite different. The stator currents to produce these torque curves are indicated by the dotted lines of Fig. 11.

When an induction motor is plugged to standstill by reversing the a-c. phase rotation the slip of the rotor changes from $s = 2$ to $s = 1$. The torque curve for these conditions is indicated in curve B of Fig. 11. As a comparison of braking capabilities under a-c. and d-c. plugging, therefore, we must compare curves B and C. The calculations shown to the right of Fig. 11 indicate that for the same average retarding torque, or in other words to stop the motor in the same time, the d-c. current would be 14.55 amperes whereas the a-c. current would have an r.m.s. value of 27.8 amperes. The heating of the stator under retardation due to stator current is indicated in the calculations. A better a-c. speed-torque curve, as regards available torque for retardation, could be produced by this motor by the use of a higher resistance rotor. The stator heating would still be in favor of the d-c. braking and the running losses of the motor would be materially increased.

D-c. braking thus gives a cooler motor under conditions of starting and stopping not only from the question of stator heating produced during the retardation period indicated above but also due to the absence of the high-frequency iron losses, both in rotor core and teeth, which are present under a-c. plugging.

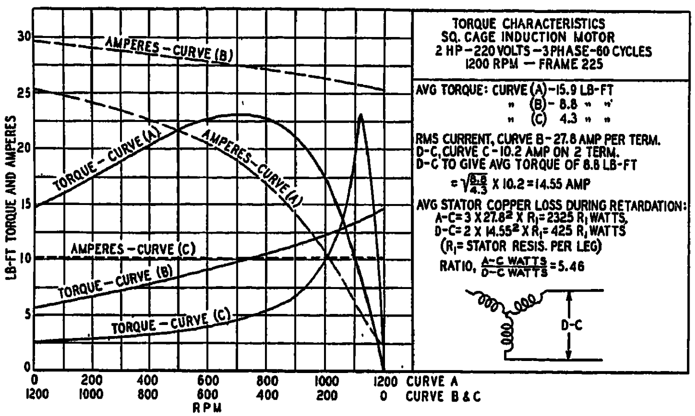

FIG. 11

With regard to the question of the relative merits of d-c. and a-c. motors for rapid stopping and reversing service, each type has advantages and disadvantages with respect to the other. I believe the demand for a-c. motors has come chiefly due to the fact that the a-c rotor is more sturdy, demands less maintenance, operates with lower-cost control and more rapid-acting control. The a-c. rotor lends itself better to lower values of WR^2 but the torque advantage of the d-c. motor together with its reduced stator heating and the locating of the secondary loss outside of the motor tend to restore a balance between the two types.

Dynamic Braking of Synchronous Machines

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Associate, A.I.E.E.

and

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INTRODUCTION AND SCOPE

THERE is a number of applications of synchronous machines where it is desirable to stop the rotation as quickly as possible. The electric methods of accomplishing this are plugging and dynamic braking. Plugging consists of reversing the phase rotation of the voltage applied to the armature winding. Dynamic braking consists of short-circuiting the armature through an external resistor and maintaining field excitation. In this paper these two methods are compared and the results of an analytical treatment of dynamic braking are given. The paper is new to the extent that it treats variable speed short-circuits.

GENERAL DISCUSSION

Independent of the type of braking used, it is necessary to convert the stored energy in the rotating system into some other form, usually heat. Analyses of a number of particular applications of synchronous motors to steel and rubber mills, where quick stops are necessary, have shown that practically all of the stored energy in such systems is in the motor rotor. The normal means of dissipation of this energy are the windage, friction, copper and core losses of the motor, and the friction of the rolls. Generally, unless the rolls are loaded, the amount of energy dissipated in them is negligible, being of the same order of magnitude as their stored kinetic energy. The neglect of both these factors is therefore a compensating error. The other means of energy dissipation are functions of the method used.

FIG. 1—TYPICAL APPLICATION WHERE BRAKING IS NECESSARY

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In plugging, the phase rotation of the supply voltage is reversed, the performance then being similar to that during starting except that the motor slip varies from two to one instead of from one to zero. At the time the speed becomes zero, the power must be removed to prevent a reversal of rotation. This method of phase reversal is subject to several outstanding objections, the most prominent of which are: first, unless the power supply is large, the system disturbance resulting from the switching operations may be very undesirable; second, the torque developed for a usual motor is small, thus limiting the rate at which the system can be stopped unless a specially designed amortisseur winding is used. This special design of amortisseur winding, beneficial to stopping, frequently is detrimental to other machine characteristics; third, if reversal is to be prevented, the power supply must be accurately controlled so that it may be removed at the instant the motor reaches zero speed. This introduces complications in the control circuits which can be avoided by other stopping methods.

In dynamic braking the armature is short-circuited through an external resistor and field excitation is maintained. The operation is that of a generator short-circuited through an external resistor. The theory of such operation from the standpoint of constant speed has been thoroughly treated in previous publications. The dynamic braking cycle differs from these treatments in that as the rotational energy of the system is dissipated, the speed of the machine decreases. The rate of this dissipation depends greatly upon the resistance used, as will be shown in the section on analytical results.

In order to present a comparison of the two methods, Table I has been prepared showing the number of revolutions made before stopping and the time in seconds required for each of the two methods.

TABLE I

Motor speed r.p.m.	Plugging		Dynamic braking	
	Rev.	Time	Rev.	Time
1,200	15.60	1.72	9.00	.98
600	5.50	1.21	4.32	.95
300	2.90	1.28	2.40	1.05
150	1.65	1.45	1.41	1.24
72	1.02	1.87	.85	1.56

The figures are based on an average 1,000-hp. unity-power-factor, mill-type motor. They represent calculated results based on the theory which follows.

ANALYTICAL RELATIONS

To determine the relations during the braking cycle an expression for the instantaneous armature current is

obtained from the vector diagram of a suddenly short-circuited generator with known speed decrease. The instantaneous torque in synchronous kilowatts is obtained from the armature current and effective circuit resistance. This is equated to the rate of change of kinetic energy due to speed reduction. There results a differential equation which when solved gives the speed-time curve in terms of the machine constants. Experience has shown that there are two satisfactory methods of solving this equation. The first, based upon the assumption of constant effective excitation, gives an equation for the speed-time curve

$$t = \frac{2H}{e_d'^2 r}\left\{\frac{x_d'^2}{2}(1-n^2) - r^2 \log n + \frac{r^2}{2}\left(\frac{x_d'}{x_q}-1\right)^2 \log\left(\frac{n^2 x_q^2 + r^2}{x_q^2 + r^2}\right)\right\}$$

where n is the per-unit speed.

The number of revolutions made by the machine upon reaching a given speed is then obtained by changing the variable in the speed-time equation and integrating. This is

$$R = \frac{N_o H}{30\, e_d'^2 r}\left\{ r^2(1-n) + \frac{x_d'^2}{3}(1-n^3) - r^2\left(\frac{x_d'}{x_q}-1\right)^2\left[(1-n) - \frac{r}{x_q}\left\{\tan^{-1}\left(\frac{x_q}{r}\right) - \tan^{-1}\left(\frac{n x_q}{r}\right)\right\}\right]\right\}$$

The total revolutions made to stop are found by placing correct boundary conditions in the above equation, and solving. The result is:

$$R_s = \frac{N_o H}{30\, e_d'^2 r}\left\{ r^2 + \frac{x_d'^2}{3} - r^2\left(\frac{x_d'}{x_q}-1\right)^2 \left(1 - \frac{r}{x_q}\tan^{-1}\frac{x_q}{r}\right)\right\}$$

The optimum value of resistance to be used in order that the revolutions to stop are a minimum, considering all of the machine quantities to remain constant, is obtained by differentiating R_s with respect to r and neglecting the less significant terms. This value is:

$$r_o = \frac{x_d'}{\sqrt{3}}$$

The second method of solution is based upon variable excitation with an assumption regarding the manner of variation. Analysis of a number of oscillograms taken during the dynamic braking cycle has shown that the field current can be represented very closely by a single exponential form, the time constant however being shorter than that of the field under short-circuited armature conditions. Using this assumption there results a relation between the machine quantities, speed and time

$$\frac{E_f^2}{r_f^2}t - \frac{2E_f\left(I_B - \frac{E_f}{r_f}\right)}{r_f\,\alpha}(\epsilon^{-\alpha t} - 1) - \frac{\left(I_B - \frac{E_f}{r_f}\right)^2}{2\alpha}(\epsilon^{-2\alpha t} - 1) = \frac{2HI_{fo}^2}{r}\left\{\frac{x_d^2}{2}(1-n)^2 - r^2\log n + \frac{r^2}{2}\left(\frac{x_d}{x_q}-1\right)^2 \log\left(\frac{n^2 x_q^2 + r^2}{x_q^2 + r^2}\right)\right\}$$

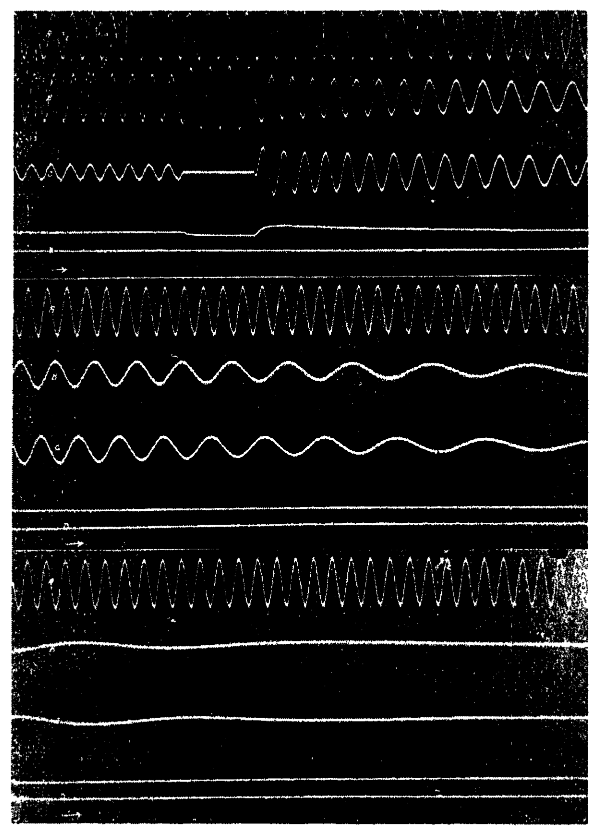

FIG. 2—DYNAMIC BRAKING CYCLE

500 hp., 40 pole, 180 r.p.m., 0.8 power factor
Curve A —60-cycle timing wave
Curve B —terminal voltage
Curve C —armature current
Curve D —field current

In this equation I_B is the field current after disconnecting from the line. All subscripts f refer to the field.

The left hand side of the equation has only time functions, and the right hand side has only speed functions. Being of transcendental character, no explicit solution is available, but the desired result may be obtained by plotting the two sides of the equation and finding the time and corresponding speed for which they are equal.

Discussion of Results

The theoretical results are based on the premise that saturation may be neglected, but their application to a practical machine must include saturation effects in the determination of the initial conditions and in the determination of the instantaneous excitation. This is evident, because regardless of the initial terminal voltage applied, and the initial field current, there is some point during the speed decrease at which normal flux is reached. As the machine passes this point, saturation plays an increasingly greater part in the effective excitation. Since this excitation enters the determination of the stopping revolutions as the square, its accurate calculation is imperative. Satisfactory results would not be possible in many practical applications if saturation were omitted.

The assumption of constant effective excitation will embrace a large majority of applications, in fact will be sufficiently accurate for most calculations.

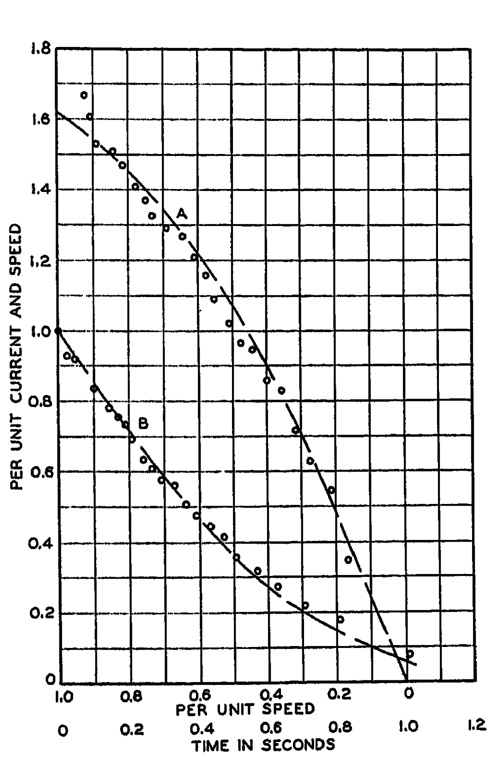

Fig. 3—Current and Speed Characteristics During the Braking Cycle Shown in Fig. 2

Curve *A*—per-unit current *vs.* unit speed

$$i_n = e_{d'} \left\{ \frac{x_q^2 + \left(\frac{r}{n}\right)^2}{\left(\frac{r}{n}\right)^2 + x_{d'} x_q} \right\}^{1/2}$$

Test points indicated by small circles

Curve *B*—per-unit speed *vs.* time

$$t = \frac{2H}{e_{d'}^2 r} \left[\frac{x_{d'}^2}{2} (1 - n^2) - r^2 \log n + \frac{r^2}{2} \left(\left(\frac{x_{d'}}{x_q} \right) - 1 \right)^2 \log \left\{ \frac{n^2 x_q^2 + r^2}{x_q^2 + r^2} \right\} \right]$$

Test points indicated by small circles

In the case of a braking cycle being initiated with the machine under load, it is interesting to note that the revolutions to stop, due to the rate of electrical energy dissipation will usually be greater than would occur under initial no-load conditions. The presence of the shaft load, if it continues, will of course aid in the stopping and bring the machine to rest sooner than the no-load condition in spite of the fact that the rate of electrical energy dissipation is less.

The effect of power factor is to increase the effective excitation and consequently improve the stopping cycle. If, however, the power factor necessitates a larger diameter machine than could otherwise be used, the increased mechanical energy storage may more than offset the gain obtained from a greater rate of dissipation. The proper proportioning of a particular machine depends upon these two factors, and to obtain good results a careful balance must be found.

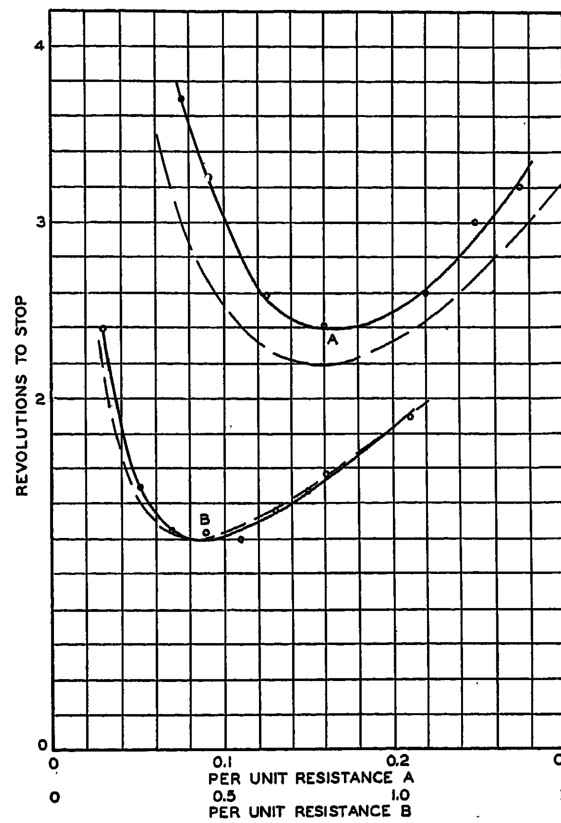

Fig. 4—Effect of External Resistance on Stopping Revolutions

Curves *A*—600 hp., 12 pole, 600 r.p.m., 0.8 power factor
Curves *B*—500 hp., 40 pole, 180 r.p.m., 0.8 power factor

$$R_S = \frac{N_0 H}{30\, e_{d'} r} \left[r^2 + x_{d'}^2 - r^2 \left(\frac{x_{d'}}{x_q} - 1 \right)^2 \left\{ 1 - \frac{r}{x_q} \tan^{-1} \left(\frac{x_q}{r} \right) \right\} \right]$$

Test curves in full lines
Calculated curves broken lines

Comparison Between Test and Calculated Results

Fig. 2 shows an oscillogram of the relations during the dynamic braking of a 500-hp., 40-pole, 180-r.p.m., 0.8-power factor synchronous motor whose constants are:

$x_d = 1.45 \quad x_q = 1.02 \quad x_d' = 0.65 \quad e_d' = 1.34 \quad N_o = 180$

H = stored energy per kva. = 0.493 seconds

r = total per-unit armature resistance = 0.53

Fig. 3 shows a comparison between test and calculated current-speed and speed-time curves from the oscillogram of Fig. 2. The agreement between the curves is quite satisfactory. Fig. 4 shows test and calculated revolutions to stop *vs.* per-unit armature resistance on two synchronous motors, one of which is the one given previously and the other is a 600-hp., 12-pole, 600-r.p.m., 0.8-power factor machine whose constants are:

$x_d = 0.89 \quad x_q = 0.52 \quad x_d' = 0.22 \quad e_d' = 1.27$

$H = 0.762 \quad N_o = 600$

The general shapes of the test and calculated curves are similar although there is a fairly constant difference between the curves on the 12-pole motor.

Of particular interest is the fact that the agreement between test and calculated values at the optimum resistance is quite good. This is true of the revolutions to stop as well as the current-speed and speed-time curves. As the resistance is increased or decreased with respect to the optimum the agreement is less satisfactory. The minimum revolutions as determined by the equation for r_o are 2.45 for the 12-pole motor and 1.22 for the 40-pole motor. The test curves give respectively 2.42 and 1.20.

Conclusions

Accurate and practical formulas for determining the number of revolutions and time required to stop are presented, thus enabling the prediction of dynamic braking performance comparable with that of other machine characteristics.

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Discussion

C. C. Shutt: The adaptability of synchronous motors to dynamic braking is doubtless one factor which has influenced their rather general application to rubber mills and similar drives. An additional point in favor of dynamic braking over plugging is that the time required for the control to function, in making the transfer from running to braking possible, is usually less for dynamic braking.

For several years the writer has used an approximate set of equations based on the round rotor theory, which gives the speed-time characteristics, the revolutions to stop and the best value of resistance. These equations are the same as those given by the authors when the direct and quadrature axis reactances are made equal. Also, the value of resistance to get the minimum number of revolutions to stop is the reactance divided by the square root of 3.

The question has always been, what value of reactance to use. The present authors have used the transient reactance. This assumes the flux in the machine to remain substantially constant from the start of the braking cycle. This assumption does not appear to be justified. The current will decrease for two reasons. The first is due to the increase in effective resistance of the armature circuit as indicated in the formula under Fig. 3 of the present paper. The other is due to normal decrement which would occur even though the speed remains constant. The time constant is, of course, modified by the resistance in the armature circuit.

The writer had always based the resistance on a value of reactance somewhat higher than the transient as being more nearly theoretically correct. Factory tests have led to the same conclusion which may be deduced from Fig. 4, namely that when a little more than the transient reactance is used for the basis of arriving at the resistance value, the value itself may be varied $\pm$ 30 or 40 per cent with only a 6 to 12 per cent in total revolutions to stop. This fact is important in that for practical purposes it eliminates the necessity of precise determination of the value of braking resistor.

If the value of resistance for shortest round travel could be obtained from the authors' expression based on variable excitation, it should be very nearly the correct value, as the expression itself appears to be correct in form. The solution of this equation and the comparison of the results with those obtained by the previous method would be very interesting.

C. E. Kilbourne: Mr. Shutt has raised the question of what is the correct value of reactance to use in the braking cycle and has suggested a value somewhat higher than the transient used in this presentation. He is correct in saying that the effective reactance is larger than the transient reactance, but the difference between a reactance found by taking a value which is determined from the minimum braking travel and the transient value is small. This is so because the majority of the speed decrease occurs in the first fraction of a second at the start of the cycle and is nearly governed by transient conditions. It is true that a higher reactance dominates the end parts of the action but as far as total effect is concerned it does not have much weight. Fig. 3 bears out this statement.

As stated in the paper, the assumption of constant effective excitation will be sufficiently accurate for most calculations. A number of comparisons made between results obtained by the approximate and more accurate equations seldom showed more than 10 per cent difference in total revolutions as obtained by the two methods, thereby again indicating that the assumption of transient reactance is nearly correct.

Current Propagation in Electric Railway Propulsion Systems

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I. Introduction

THE study of current propagation in electric railway propulsion systems is important to the telephone engineer engaged in inductive coordination of railway and telephone facilities; it also is of interest, of course, to the railroad engineer because of its effect on network impedances and voltages between track and ground. The present paper presents a systematic treatment of current propagation in the tracks and associated conductors of electric railway propulsion systems. The tracks, being continuously in contact with the earth through the track ballast, allow current to leak into the earth, and track currents and voltages to ground vary along the tracks. The present treatment is limited to systems in which the tracks and other leaky conductors may be represented by a single conductor; for convenience the single conductor will be referred to as a track, with the understanding that it may be the representative of a number of tracks or of tracks with associated ground wires having frequent connections to tracks or ground, whenever this is permissible.

The general equations of propagation in a track in the presence of a conductor carrying a fixed current used herein have been known and in use for some time,[1] they are given in section II, together with a discussion of their interpretation and limitations. In section III they are used to develop the properties of a basic circuit consisting of a conductor of finite length connected to the track, which is continuous and of infinite length. By means of superposition complex systems of circuits may be built up of basic circuits and the currents in the conductors determined by the self and mutual impedances of basic circuits in conjunction with the impedance diagram of the remaining railway network. The current distribution in the track due to each conductor current is given by the basic circuit solution and the resultant may then be obtained by superposition. Track discontinuities may also be included by superposition and details are given for single series discontinuities formed by a series track impedance, and for double shunt discontinuities, formed by connecting impedances between track and ground. The latter includes the special case in which the track is terminated outside the conductor span by arbitrary impedances, giving in the two limits of zero and infinite terminal impedances, the cases of tracks solidly grounded and without grounds at the terminals. The self- and mutual-impedances of propulsion circuits involving track discontinuities are formulated and may be employed in the railway network diagram when discontinuities are involved. The analysis given is applicable to any railway system in which the tracks or tracks and associated ground wires having frequent connections to track or grounds may be represented by a single conductor. A description of a method of employing the basic circuit in determining cumulative induction curves which include the effect of distribution of current along the track and by means of which voltages in communication lines may be determined is given in section III.

The use of superposition is convenient for numerical work since curves and tables may be prepared applying to a variety of conditions, and since parts of a given system may be studied apart from the remainder and the effect of alterations in these parts determined without re-solving the whole system. It also simplifies the study of formal properties since any desired complexity may be secured from elementary circuits whose properties can thus be determined without loss of generality.

II. Equations of Propagation

The differential equations of propagation in a track 2 having an earth-return series impedance z_{22}, and a shunt admittance to ground g, in the presence of a second conductor 1 containing a fixed current in opposite direction to the track current, whose mutual impedance with earth return to the track with earth return is z_{12}, all impedances being per unit length, are as follows:

$$z_{22}I_2 - z_{12}J = -\frac{dV_2}{dx} \qquad (1)$$

$$gV_2 = -\frac{dI_2}{dx}$$

where

J and I_2 = currents in conductor 1 and track, respectively
V_2 = track voltage to ground
x = distance along track in the direction of the track current.

The solutions of these equations may be written in the following form:

$$\begin{aligned} I_2 &= ae^{-\gamma x} - be^{\gamma x} + \mu J \\ V_2 &= kae^{-\gamma x} + kbe^{\gamma x} \end{aligned} \qquad (2)$$

where

a,b = integration constant to be determined from boundary conditions

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1. These equations were apparently first published by H. Pleijel as Part II of a report to the Swedish Royal Railway Administration "Undersokningar rorande Svagstromsstorningar vid med Einfasstrom drivna Electriska Baner," *A. B. Svenska Teknologforeningens*, Stockholm, 1919.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

k = characteristic impedance $= \sqrt{z_{22}/g}$

γ = propagation constant $= \sqrt{z_{22}g}$

μ $= z_{12}/z_{22}$

The differential equations (1) are the equations of classical transmission line theory and equations (2) are thus subject to the restrictions that the propagation constant γ be small compared to unity, in c.g.s. units, and that the circuit terminals be avoided; that is, the equations do not hold near the terminals. Even if these restrictions are maintained, the equations are not theoretically rigorous, since the voltage between points on the earth coextensive with the track is either ignored or supposed to vary linearly with V. It should also be noted that the impedance z_{22} of the track circuit contains a component dependent upon the rail permeability and thus upon the current density, which varies with length. The external component of z_{22} is dependent upon the circuit length as with any earth return circuit.

Thus, the use of the equations requires a justification apart from their theoretical background. For present purposes, it is sufficient to note that it has been found experimentally that the track current is propagated according to the exponential law in equations (2) within engineering accuracy. Equations (2) may be adopted, in the lack of more rigorous solutions, on the grounds of formal simplicity and sufficient accuracy for most engineering purposes.

The ratio μ, the propagation constant γ, and the characteristic impedance k depend on the impedances z_{12}, z_{22} and the shunt admittance g. Because of the semi-empirical character of the equations of propagation, values of μ, γ and k should be determined from measurements on a track or system of tracks in actual working position, suitably chosen mean values being taken if necessary; the values of z_{12}, z_{22} and g then follow from them, since $z_{22} = k\gamma$, $g = \gamma/k$, $z_{12} = \mu z_{22}$. It is outside the scope of this paper to discuss the measurement or calculation of these quantities; it may be added, however, that g is, in general, purely conductance (at low frequencies) and its range is from 0.5 to 2.0 mhos per mile per track. Estimates of z_{12} and z_{22} may be made from the configuration of the conductors and the size of the tracks, employing the formulas for self- and mutual-impedances of ground-return circuits,[2] and measured values of the rail constants.

It may be noted here that the integrals of track current and voltage with respect to x may be written from equations (1) as follows:

$$\int_{x_1}^{x_2} I_2 dx = \mu\,(x_2 - x_1)\,J + \frac{1}{z_{22}}\,(V_2\,(x_1) - V_2\,(x_2))$$
$$\int_{x_1}^{x_2} V_2 dx = g^{-1}\,(I_2\,(x_1) - I_2\,(x_2)\,) \qquad (1a)$$

2. "Wave Propagation in Overhead Conductors with Ground Return," John R. Carson, *Bell System Technical Journal*, V. 5, October 1926, pp. 539-554. "Mutual Impedance of Grounded Wires Lying on the Surface of the Earth," Ronald M. Foster, *Bell System Technical Journal*, V. 10, pp. 408-419, July 1931.

III. The Basic Conductor-Track/Earth Circuit*

Derivation of Basic Circuit Properties

The circuit consisting of a conductor of length s carrying a current J and connected to a continuous infinite track is taken as the basic circuit since it involves the greatest degree of continuity in the track and is easily adapted to modifications for discontinuities, such as track terminations, track feeders, etc. The circuit is shown in Fig. 1.

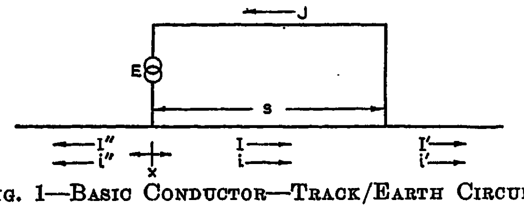


Fig. 1—Basic Conductor—Track/Earth Circuit

The track currents and voltages to ground in the three sections are taken as follows:

$$I \;= ae^{-\gamma x} - be^{\gamma x} + \mu J$$
$$V \;= kae^{-\gamma x} + kbe^{\gamma x} \qquad 0 \leqq x \leqq s \qquad (3)$$
$$V' = kI' = ka'e^{-\gamma(x-s)} \quad s \leqq x \qquad (4)$$
$$V'' = kI'' = ka''e^{-\gamma|x|} \quad 0 \geqq x \qquad (5)$$

The boundary conditions are the continuity of current and voltage at points 0 and s, that is:

$$J - I\,(o) = I''\,(o) \qquad (6)$$
$$V\,(o) = V''\,(o)$$
$$J - I\,(s) = -\,I'\,(s)$$
$$V\,(s) = V'\,(s)$$

which when written out by means of equations (3), (4) and (5) are as follows:

$$(1-\mu)\,J - a + b = a'' \qquad (6a)$$
$$a + b = a''$$
$$(1-\mu)\,J - ae^{-\gamma s} + be^{\gamma s} = -\,a'$$
$$ae^{-\gamma s} + be^{\gamma s} = a'$$

The solutions of these equations are:

$$a \;= \frac{1}{2}\,(1-\mu)\,J \qquad (7)$$

$$b \;= -\frac{1}{2}\,(1-\mu)\,e^{-\gamma s}\,J = -\,ae^{-\gamma s}$$

$$a' = -\,a'' = -\frac{1}{2}\,(1-\mu)\,(1-e^{-\gamma s})\,J$$

All voltages, currents, and properties of the basic circuit may now be written out; the formulas are conveniently collected in Table I.

*The dash (—) is used to denote series connection and the slant (/) parallel connection. Thus, the expression above means a circuit consisting of "conductor" as one side with return by track and earth in parallel. This notation will be followed throughout.

TABLE I—CURRENTS AND VOLTAGES IN BASIC CIRCUIT (SEE FIG. 1)

Track Currents:

$$I = \mu J + \frac{1}{2}(1-\mu)\left(e^{-\gamma x} + e^{-\gamma(s-x)}\right) J$$

$$I' = -\frac{1}{2}(1-\mu)\left(1 - e^{-\gamma s}\right) e^{-\gamma(x-s)} J$$

$$I'' = \frac{1}{2}(1-\mu)\left(1 - e^{-\gamma s}\right) e^{-\gamma|x|} J$$

Earth Currents:

$$i = J - I = \frac{1}{2}(1-\mu)\left(2 - e^{-\gamma x} - e^{-\gamma(s-x)}\right) J$$

$$i = -I'$$
$$i'' = -I''$$

Minimum and Average Track Current:

$$I_{min} = \mu J + (1-\mu)\, e^{-\gamma s/2} J$$

$$\bar{I} = \frac{1}{s}\int_0^s I\,dx = \mu J + (1-\mu)\left(\frac{1-e^{-\gamma s}}{\gamma s}\right) J$$

Track Voltages to Ground:

$$V = \frac{1}{2} k (1-\mu)\left(e^{-\gamma x} - e^{-\gamma(s-x)}\right) J$$

$$V' = -\frac{1}{2} k (1-\mu)\left(1 - e^{-\gamma s}\right) e^{-\gamma(x-s)} J$$

$$V'' = \frac{1}{2} k (1-\mu)\left(1 - e^{-\gamma s}\right) e^{-\gamma|x|} J$$

Integrals of Track Currents:

$$\int_{x_1}^{x_2} I\,dx = \mu(x_2 - x_1) J + \frac{1}{z_{22}}\left[V(x_1) - V(x_2)\right]$$

$$\int_{x_1}^{x_2} I'\,dx = \frac{1}{z_{22}}\left[V'(x_1) - V'(x_2)\right]$$

$$\int_{x_1}^{x_2} I''\,dx = \frac{1}{z_{22}}\left[V''(x_1) - V''(x_2)\right]$$

$$\int_0^s I\,dx + \int_s^\infty I'\,dx - \int_0^\infty I''\,dx = \mu s J$$

Conductor—Track/Earth Impedance: (Per Unit Length)

$$\begin{aligned} Z_{11} &= E/(sJ) \\ &= Z(1-\nu 2)(1-2) \\ &\qquad \left(\nu = \frac{1}{sJ}\int_0^s I\,dx\right) \\ &= z_{11} - z_{12} + \nu(z_{22} - z_{12}) \\ &= z_{11} - \mu z_{12} + z_{22}(1-\mu)^2\left(\frac{1-e^{-\gamma s}}{\gamma s}\right) \end{aligned}$$

$$\lim_{s\to 0} Z_{11} = z_{11} + z_{22} - 2z_{12}$$

$$\lim_{s\to\infty} Z_{11} = z_{11} - \mu z_{12} = z_{11} + z_{22} - 2z_{12} - (1-\mu)^2 z_{22}$$

Before discussing the formulas it may be noted that the track current may be resolved into three components (*i*) a constant current μJ in the section coextensive with the conductor (*ii*) exponentially propagated currents $ae^{-\gamma|x|}$ flowing each way from point 0, x being measured from this point (*iii*) exponentially propagated currents $(-be^{\gamma s})\, e^{-\gamma|y|}$ flowing each way from point s, y being measured from s. Since $a = -be^{\gamma s}$, components (*ii*) and (*iii*) are of equal maximum value. The resolution is suggested by the relations $a' = ae^{-\gamma s} + be^{\gamma s}$ and $a'' = a + b$ and by the form of the current equations. The current μJ is the limit approached by the track current as the section length is made infinite, the currents $ae^{-\gamma x}$ and $-be^{\gamma(s-x)}$ are the "direct" and "reflected" waves produced by the terminals. Another decomposition which is physically suggestive[3] is the division into component currents J introduced in the track at the conductor terminals, and a component driven by induction from the trolley. The former flow each way from the terminals propagated exponentially, that is, the components are

$$\frac{1}{2} J e^{-\gamma|x|} \text{ and } \frac{1}{2} J e^{-\gamma|y|}$$

where x and y are measured as above. The component driven by induction from the trolley is:

$$I = \frac{1}{2}\mu\left(2 - e^{-\gamma x} - e^{-\gamma(s-x)}\right) J$$

$$I' = \frac{1}{2}\mu\left(1 - e^{-\gamma s}\right) e^{-\gamma(x-s)} J$$

$$I'' = -\frac{1}{2}\mu\left(1 - e^{-\gamma s}\right) e^{-\gamma|x|} J$$

Table I gives the formulas for track currents, track voltages to ground, earth currents, minimum, average and integral track currents, maximum and average earth currents in the section spanned by the conductor, 0 to s, and finally the conductor-track/earth voltage and unit impedance.

The integral of track current between the limits $-\infty$ and $+\infty$ is $\mu s J$, since both direct and reflected waves, each of which flows in both directions as noted above, are cancelled over this range; the same value of the integral of track current is obtained as will be shown later when one or more track shunt discontinuities is present. The integral of track current over the same infinite region for any number of conductors individually connected to the track is the sum of their separate contributions, that is:

$$\int_{-\infty}^{\infty} I\,dx = \mu_1 s_1 J_1 + \mu_2 s_2 J_2 + \ldots + \mu_n s_n J_n$$

The conductor-track/earth unit impedance is derived from the following formula:

$$Z_{11} = z_{11} - z_{12}\frac{1}{sJ}\int_0^s I\,dx + z_{22}\frac{1}{sJ}\int_0^s I\,dx - z_{12} \quad (8)$$

$$= z_{11} - z_{12} + (z_{22} - z_{12})\,\nu$$

3. The first of the above resolutions of currents is given by H. Pleijel *loc cit.*; the second by E. R. Benda and H. Voightlander, "Der Spannungsabfall in Fahrleitungen und Schienen elektrischer Bahnen," *Wiss. Veroff. a. d. Siemens-Konzern*, **10**, 78-90, who also note the first.

where

$$\nu = \frac{1}{sJ}\int_0^s I\,dx$$

This formula can be written in the more compact form

$$Z_{11} = Z_{12:12} = Z_{(1-\nu 2)(1-2)} \qquad \textbf{(8a)}$$

where the second line of (8) is the expanded form of (**8a**)[4]; the subscripts being obtained by multiplying the parenthesis algebraically with $z_{\nu jk}$ interpreted as νz_{jk}.

For the basic circuit the averaging factor ν is given by

$$\nu = \mu + (1-\mu)\left(\frac{1-e^{-\gamma s}}{\gamma s}\right) \qquad (9)$$

and

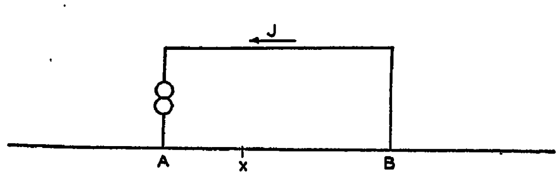
$$Z_{11} = z_{11} - \mu z_{12} + z_{22}\,(1-\mu)^2\left(\frac{1-e^{-\gamma s}}{\gamma s}\right) \qquad (10)$$

which has the following limits

$$\lim_{s=0} Z_{11} = z_{11} + z_{22} - 2z_{12} \qquad \textbf{(10a)}$$

$$\lim_{s=\infty} Z_{11} = z_{11} - \mu z_{12} = z_{11} + z_{22} - 2z_{12} - (1-\mu)^2 z_{22} \qquad \textbf{(10b)}$$

The first of the limits is physically evident as the impedance of a metallic loop; all of the conductor current



$$i(x) = \frac{1}{2}(1-\mu)\,[\alpha\,(\overline{Ax}) \pm \alpha\,(\overline{Bx})]\,J$$

FIG. 2—EARTH CURRENT IN TERMS OF PARAMETER $\alpha(x)$; $\alpha(x) = 1 - e^{-\gamma x}$; PLUS SIGN IN FORMULA WHEN x IS BETWEEN A AND B, MINUS SIGN OTHERWISE; DISTANCES $\overline{Ax}$ AND $\overline{Bx}$ POSITIVE

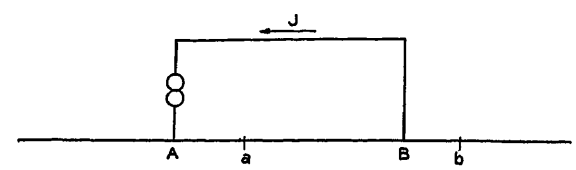
returns in the track. In the second the track current is μ (for unit conductor current) and the track voltage drop is zero since $z_{22}I - z_{12}J = 0$, or, otherwise, since there is no leakage along the track. The second form of (**10b**) shows the maximum difference in Z_{11} due to change of s to be $(1-\mu)^2 z_{22}$.

In systematic calculation of currents, it is convenient to deal with earth currents; either quantity, track or earth current, determines the other: by subtraction from the conductor current within the conductor span, that is, $I + i = J$, or by reversing sign $(I + i = 0)$, outside the conductor span. The earth current itself and its average as dependent on x are each determined in terms of a single parameter, namely:

$$\alpha(x) = 1 - e^{-\gamma x} \qquad \text{— earth current} \qquad \textbf{(11)}$$

$$\beta(x) = \frac{1}{x}\int_0^x \alpha(x)dx = 1 - \frac{1-e^{-\gamma x}}{\gamma x} \text{— average earth current} \qquad \textbf{(12)}$$

The current at any point is the sum of the products, each with proper sign, of two values of $\alpha\,(x)$ by



$$i = \frac{1}{\overline{ab}}\int_a^b i(x)dx$$

$$= \frac{1}{2\,\overline{ab}}(1-\mu)\,[\overline{Ab}\,\beta\,(\overline{Ab}) - \overline{Aa}\,\beta\,(\overline{Aa}) + \overline{Ba}\,\beta\,(\overline{Ba}) - \overline{Bb}\,\beta\,(\overline{Bb})]\,J$$

FIG. 3—AVERAGE EARTH CURRENT OVER DISTANCE $\overline{ab}$ IN TERMS OF PARAMETER $\beta(x)$, $\beta(x) = 1 - (1 - e^{-\gamma x})/\gamma x$; ALL DISTANCES, $\overline{Aa}$, $\overline{Ab}$, $\overline{Ba}$, $\overline{Bb}$ POSITIVE; a AND b ARBITRARY POINTS ON THE TRACK, b TO THE RIGHT OF a

(1/2) $(1-\mu)\,J$, as shown in Fig. 2. The formula for average currents in terms of $\beta\,(x)$ is shown in Fig. 3. The formula in Fig. 2 may be verified by inspection of the proper equations in Table I; the formula in Fig. 3 follows directly by application of the integral formula

$$\beta\,(x) = \frac{1}{x}\int_0^x \alpha\,(x)\,dx$$

after performing the integration of the current in terms of $\alpha\,(x)$.

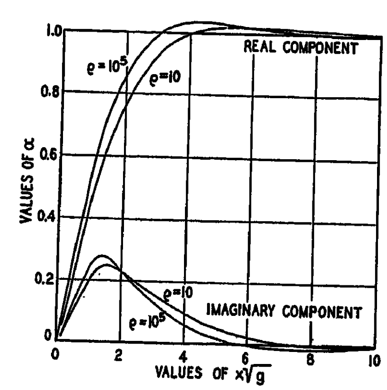


FIG. 4—EARTH CURRENT PARAMETER $\alpha(x)$ FOR SINGLE TRACK RAILROAD, 130-LB. RAILS, AS A FUNCTION OF $x\sqrt{g}$, x BEING DISTANCE IN MILES AND g CONDUCTANCE FROM TRACK TO GROUND IN MHOS PER MILE; EARTH RESISTIVITY ρ IN METER-OHMS

Curves of $\alpha\,(x)$ and $\beta\,(x)$ for a 25-cycle single-track railroad are shown in Figs. 4 and 5; these curves apply for ground resistivities of 10 and 100,000 meter-ohms to a track having rails weighing 130 lb. per yard, the track impedances being respectively $0.177 + j\,0.453$ and $0.177 + j\,0.693$ ohm per mile.

4. This notation is a modification of a notation for Neumann integrals used by G. A. Campbell: "Mutual Impedance of Grounded Circuits," *Bell System Tech. Journal* 2, 1-30 (October 1923).

Mutual Impedance of Basic Circuits

The mutual impedance of basic circuits as shown in Fig. 6 is given by the following formula:

$$
\begin{aligned}
Z_{12:32} &= Z\,[s(1 - \nu_1 2) - (s_3 - s)\,\nu_1' 2]\,(3 - 2) \\
&= Z(1 - 2)\,[s\,(3 - \nu_3 2) + (s_1 - s)\,\nu_3' 2] \\
&= s\,(z_{13} - \mu_3 z_{12}) - \frac{1}{2}\,k\,(1 - \mu_1)\,(1 - \mu_3) \\
&\quad \times [\,e^{-\gamma s} + e^{\gamma s}\,(e^{-\gamma(s_1+s_3)} - e^{-\gamma s_1} - e^{-\gamma s_3})\,] \qquad (13)
\end{aligned}
$$

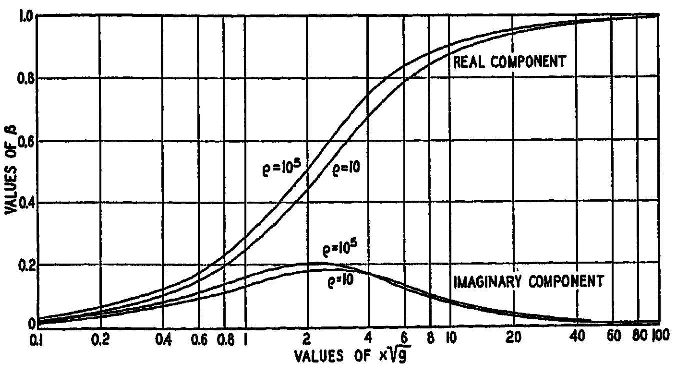


FIG. 5—AVERAGE EARTH CURRENT PARAMETER $\beta(x)$ AS A FUNCTION OF $x\sqrt{g}$, CONDITIONS AND UNITS AS ON FIG. 4

where

s_1, s_3 and s = lengths of wires 1, 3 and their overlapping portion, respectively.

$\nu_1, \nu_1', \nu_3, \nu_3'$ = average unit track currents over sections s, $s_3 - s$ with wire 1 energized and over sections s and $s_1 - s$ with wire 3 energized, respectively.

$$\mu_1 = z_{12}/z_{22}, \ \mu_3 = z_{23}/z_{22}$$

The first line of equations (**13**) gives the mutual impedance with wire 1 energized, the second with wire 3 energized; their equality follows from the reciprocal theorem, that is, $Z_{12:32} = Z_{32:12}$.

The mutual impedances of the non-coextensive portions of the wires are not included in equations (**13**) on the assumption that they are negligibly small; this is consistent with the usual practise of using limiting values for infinite length of wire-earth self- and mutual-impedances.

The current direction is the same in each wire and the voltage drop in one section of zero current, which with unit current in the other section gives the mutual impedance of the circuits, is taken positive when it is in the positive sense defined for the wire currents.

This general formula reduces to equation (**8**) or its alternates (**8a**) and (**10**) when the wires are coextensive, $s_1 = s_3 = s$, and $3 = 1$, the result being expressed per unit length. The general formula for non-overlapping circuits of lengths s_1 and s_3 separated by distance s is as follows:

$$Z_{12:32} = -\frac{1}{2}\,k(1-\mu_1)(1-\mu_3)(1-e^{-\gamma s_1})(1-e^{-\gamma s_3})e^{-\gamma s} \qquad (14)$$

The general formula for circuits of lengths s_1 and s_3, such that the former spans the latter with distance s between the terminals on the left, is as follows:

$$
\begin{aligned}
Z_{12:32} &= s_3\,(z_{13} - \mu_1 z_{23}) + \frac{1}{2}\,k\,(1 - \mu_1)\,(1 - \mu_3) \\
&\quad \times (e^{-\gamma s} - e^{-\gamma(s_1 - s)} - e^{-\gamma(s + s_3)} + e^{-\gamma(s_1 - s - s_3)}) \qquad (15)
\end{aligned}
$$

The mutual impedance of metallic circuits in the presence of the track may be derived from the above results by making up the energizing circuit of two circuits, one from each of the wires of the metallic loop, with track return and equal and opposite currents. An example of mutual impedances involving metallic circuits will be given later in connection with the three-wire system of electrification.

Application of the Basic Circuit

General. The basic circuit can be applied directly by means of superposition to building up systems of circuits in which the track is continuous and infinite; or, conversely, any system of circuits involving continuous, infinite track may be regarded as made up of basic circuits. The propulsion circuit impedances for use in railway network impedance diagrams may be determined in this way, the basic circuits being made sections of the trolley in which the current has one value. Examples will be given in a section following. The corresponding impedances when the track has discontinuities are also given later, in connection with track discontinuities. A basic circuit of length s may also be subdivided into n subcircuits of length s/n, since the currents flowing in the vertical connections between conductor and track will be in opposite direction in adjacent sections, and all vertical connections except the terminal ones carry no current and may thus be removed or retained as desired. This process is employed in the construction of a cumulative induction curve for communication lines, to be described below.

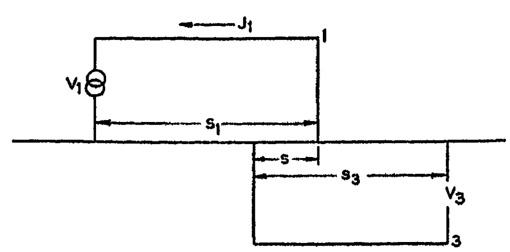


FIG. 6—MUTUAL IMPEDANCE OF OVERLAPPING BASIC CIRCUITS

Propulsion Circuit Impedances in Railway Network Diagrams. In cases involving single conductors or single-conductor equivalents of multiple conductors with track return, the formulas for self- and mutual-impedance of basic circuits given above may be em-

ployed directly in determining the propulsion circuit impedances, the sections being made up as described above. It may be noted that the mutual impedance of adjacent, *i.e.*, non-coextensive, basic circuits is generally small and possibly negligible. When a number of outgoing and return conductors are involved, the propulsion circuit impedances may be obtained by superposition of the component basic circuits energized as they are to be connected in the network. An example is shown in Fig. 7 in which there are two outgoing and two return coextensive conductors. Fig. 7 also shows the simultaneous equations in terms of the self- and mutual-basic circuit impedances by means of which conductor currents may be determined, when the system is energized as shown. The self-impedance of the system per unit length is $V \div s\,(J_0 + J_1)$; the mutual impedance with any other system of conductors may be determined from the currents and component mutual basic circuit impedances, the total system current $J_0 + J_1$ being set equal to unity.

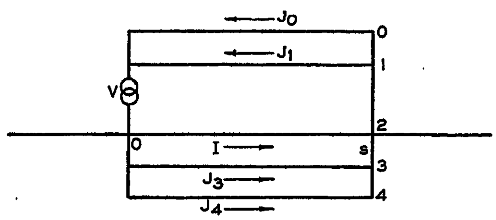


FIG. 7—A SYSTEM OF COEXTENSIVE BASIC CIRCUITS

$$
\begin{aligned}
Z_{00}J_0 + Z_{01}J_1 - Z_{03}J_3 - Z_{04}J_4 &= s^{-1}\,V \\
Z_{01}J_0 + Z_{11}J_1 - Z_{13}J_3 - Z_{14}J_4 &= s^{-1}\,V \\
-Z_{03}J_0 - Z_{13}J_1 + Z_{33}J_3 + Z_{34}J_4 &= 0 \\
-Z_{04}J_0 - Z_{14}J_1 + Z_{34}J_3 + Z_{44}J_4 &= 0
\end{aligned}
$$

where

$$
\begin{aligned}
Z_{jk} &= z_{jk} - z_{j2} + \nu_j\,(z_{22} - z_{k2}) \qquad (j, k = 0, 1, 3, 4) \\
&= z_{jk} - z_{k2} + \nu_k\,(z_{22} - z_{j2}) \\
\nu_j &= \frac{1}{sJ_j} \int_0^s I_{2j}\,dx
\end{aligned}
$$

I_{2j} = track current with conductor j carrying current J_j, all other currents zero

In the three-wire system of a-c. electrification, it is customary to replace the wires by pairs of circuits, either trolley-feeder, trolley-rail or trolley-rail, feeder-rail, the third combination trolley-feeder, feeder-rail being rarely used. Formulas for self- and mutual-impedance per unit length for coextensive portions of these circuits are shown in Table II; these formulas do not include the voltage ratios necessary because of the different working voltages of the circuits. The relations of the impedances are also shown; of the six impedances, only three are independent.

Basic Circuit Induction Curves. Cumulative induction curves are ordinarily used in the calculation of induced voltages in communication lines affected by a railroad electrification. These curves usually give the continuous sum of the induced voltages in elements of the communication line due to unit current in a railway circuit with earth-return and thus the cumulated voltage between any points on the line. In this form they

TABLE II—PROPULSION CIRCUIT IMPEDANCES, THREE-WIRE SYSTEM

$$
\begin{aligned}
Z_{TR} &= Z(T - \nu_T R)(T - R) &&= z_{TT} - z_{TR} + \nu_T\,(z_{RR} - z_{TR}) \\
Z_{FR} &= Z(F - \nu_F R)(F - R) &&= z_{FF} - z_{FR} + \nu_F\,(z_{RR} - z_{FR}) \\
Z_{TF} &= Z(T - \nu_T R - F + \nu_F R)(T - F) &&= z_{TT} + z_{FF} - 2z_{TF} \\
& &&\quad - (\nu_T - \nu_F)\,(z_{TR} - z_{FR}) \\
-Z_{TR:RF} &= Z(T - \nu_T R)(F - R) &&= z_{TF} - z_{TR} + \nu_T\,(z_{RR} - z_{FR}) \\
&= Z(T - R)(F - \nu_F R) &&= z_{TF} - z_{FR} + \nu_F\,(z_{RR} - z_{TR}) \\
Z_{TR:TF} &= Z(T - \nu_T R)(T - F) &&= z_{TT} - z_{TF} - \nu_T\,(z_{TR} - z_{FR}) \\
&= Z(T - R)(T - \nu_T R - F + \nu_F R) &&= z_{TT} - z_{TF} - z_{TR} + z_{FR} \\
& &&\quad + (\nu_T - \nu_F)\,(z_{RR} - z_{TR}) \\
-Z_{FR:TF} &= -Z(F - \nu_F R)(T - F) &&= z_{FF} - z_{TF} + \nu_F\,(z_{TR} - z_{FR}) \\
&= -Z(F - R)(T - \nu_T R - F + \nu_F R) &&= z_{FF} - z_{TF} + z_{TR} - z_{FR} \\
& &&\quad - (\nu_T - \nu_F)\,(z_{RR} - z_{FR})
\end{aligned}
$$

$$
\begin{aligned}
Z_{TR:TF} &= Z_{TR} + Z_{TR:RF} \\
-Z_{FR:TF} &= Z_{FR} + Z_{TR:RF} \\
Z_{TF} &= Z_{TR:TF} - Z_{FR:TF} &&= Z_{TR} + Z_{FR} + 2Z_{TR:RF}
\end{aligned}
$$

ν_T and ν_F are average unit track currents (for unit section) with trolley and feeder, respectively, energized alone.

Limit Cases

$\nu_T = \nu_F = 1$		$\nu_T = \mu_T,\ \nu_F = \mu_F$	
Z_{TR}	$= z_{TT} + z_{RR} - 2z_{TR}$	Z_{TR}	$= z_{TT} - \mu_T z_{TR}$
Z_{FR}	$= z_{FF} + z_{RR} - 2z_{FR}$	Z_{FR}	$= z_{FF} - \mu_F z_{FR}$
Z_{TF}	$= z_{TT} + z_{FF} - 2z_{TF}$	Z_{TF}	$= z_{TT} + z_{FF} - 2z_{TF} - (\mu_T - \mu_F)^2\,z_{RR}$
$-Z_{TR:RF}$	$= z_{TF} - z_{FR} + z_{RR} - z_{TR}$	$-Z_{TR:RF}$	$= z_{TF} - \mu_T z_{FR}$
$Z_{TR:TF}$	$= z_{TT} - z_{TF} - z_{TR} + z_{FR}$	$Z_{TR:TF}$	$= z_{TT} - z_{TF} - \mu_T(z_{TR} - z_{FR})$
$-Z_{FR:TF}$	$= z_{FF} - z_{TF} + z_{TR} - z_{FR}$	$-Z_{FR:TF}$	$= z_{FF} - z_{TF} + \mu_F(z_{TR} - z_{FR})$

are adapted to cases in which current in the railway circuit is constant along the circuit length; the variation of track current may be taken into account approximately by assuming the average track current constant over the length of track involved.

The basic circuit induction curve includes the effect of the variation of track current with length and is found by calculating the induced voltage in a given communication line taken as a whole (except, of course, for parts beyond the locality of the exposure at distances such that the induced voltage is negligible) for selected positions of a basic circuit of unit length carrying unit conductor (trolley) current. The results of these calculations are plotted with the position of the basic circuit represented by its midpoint as abscissa. The integral of the resulting curve between two points on the axis of abscissas then gives the induced voltage in the telephone line for unit conductor current between the two points, exactly as with the usual cumulative induction curve. This procedure rests on the fact noted above that a basic circuit of length s may be subdivided into n circuits of length s/n.

It should be pointed out that the induction coefficients on which this curve is based should include the effects of ground potential; the study of ground potentials is not at present sufficiently developed for this purpose and the voltages calculated may thus be less than the actual voltages. The curve is of greatest use and importance when there is a number of loads or short circuits to be considered. When there are relatively few loads and a number of exposures, the preparation of these curves may be more difficult than a direct use of average earth currents prepared for each situation it is

desired to consider, and taken from curves of the average earth current parameter β, combined with a cumulative induction curve per unit trolley-earth current.

IV. Track Discontinuities

General

Track discontinuities, in general, are of two kinds, "series," in which an impedance is connected serially in the track, or "shunt," in which the impedance is connected between track and ground. The most common example of a series discontinuity is finiteness of track length, that is, connection of infinite series impedances; grounded rail buses are examples of shunt discontinuities. These discontinuities may be superposed on the basic circuit just as basic circuits are superposed on each other. Track booster transformers, that is, transformers with windings connected serially in the trolley and track for the purpose of equalizing trolley and track currents as a means of reducing induced voltages in communication lines, are also series discontinuities and the use of superposition is an important part of the analysis of their performance.

Series Discontinuities

Fig. 8 herewith shows a series discontinuity at point s_1 within the conductor span; for generality, the discontinuity is represented as a generator. The conductor current is taken from right to left, and the track current through the additional generator following the convention used before is in opposite direction. The coordinate system for track currents produced by the conductor current starts at the generator point with variable x; for the track generator the variable is y with zero at the generator point. The simultaneous equations relating the voltages and currents of the generators are as follows:

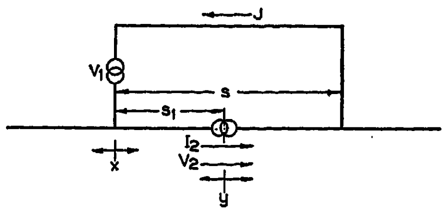


Fig. 8—Conductor—Track/Earth Circuit with Track Series Discontinuity within Conductor Span

$$Z_{11}'J + Z_{12}I_2 = V_1 \qquad (16)$$
$$Z_{12}J + Z_{22}I_2 = V_2$$

The impedances in these equations are defined as follows: Z_{11}' is the impedance of the conductor-track/earth circuit with the track broken at s_1 ($I_2 = 0$); Z_{12} is the mutual impedance of conductor-track/earth and track-earth circuits, that is, the voltage drop across a break in the track at s_1 ($I_2 = 0$) in the direction of I_2 with J unity, or the voltage drop across a break in the trolley ($J = 0$) with I_2 unity; Z_{22} is the self-impedance of the infinite track-earth circuit, as looked into from the break at s_1.

Since with zero trolley current the track current is propagated exponentially in each direction Z_{22} and Z_{12} from the first definition may be written down directly as follows:

$$Z_{22} = 2k$$

$$Z_{12} = (z_{22} - z_{12}) \left\{ \int_0^{s_1} e^{-\gamma y}\, dy + \int_0^{s-s_1} e^{-\gamma y}\, dy \right\} - Z_{22}$$
$$= k\,(1-\mu)\,(2 - e^{-\gamma s_1} - e^{-\gamma(s-s_1)}) - 2k$$

It may be noted that the formulation of this impedance is easier than that corresponding to the second definition to which it is equal by the reciprocal theorem.

Z_{11}' may be formulated indirectly as follows. With $V_2 = 0$, the basic circuit is restored and

$$I_2 = -Z_{12}J/Z_{22}$$
$$= \left[\mu + \frac{1}{2}\,(1-\mu)\,(e^{-\gamma s_1} + e^{-\gamma(s-s_1)}) \right] J$$

which agrees with the basic circuit track current as given in Table I. Conversely, the product of the known basic circuit track current by the track-earth series impedance gives the mutual impedance Z_{12} with sign reversed and is a third means of finding this quantity.

Z_{11}' is now given by the first equation of (16), since with $V_2 = 0$ and hence $I_2 = -Z_{12}J/Z_{22}$, $V_1 = Z_{11}J$ where Z_{11} is the basic circuit conductor-track/earth self-impedance. The result is

$$Z_{11}' = Z_{11} + Z_{12}^2/Z_{22}$$
$$= s \left\{ z_{11} - \mu z_{12} + z_{22} \frac{(1-\mu)^2 (1-e^{-\gamma s})}{\gamma s} + z_{22} \frac{[2\mu + (1-\mu)\,(e^{-\gamma s_1} + e^{-\gamma(s-s_1)})]^2}{2\gamma s} \right\} \qquad (17)$$

When the break is outside the conductor span at distance s_1 to the right of the origin of coordinates for the conductor current, the impedance of the conductor-track/earth circuit is as follows:

$$Z_{11}' = s \left\{ z_{11} - \mu z_{12} + z_{22}\,(1-\mu)^2 \left(\frac{1-e^{-\gamma s}}{\gamma s} \right) \times \left[1 + \frac{1}{2} e^{-2\gamma(s_1-s)} (1-e^{-\gamma s}) \right] \right\} \qquad (18)$$

The mutual impedance of collinear conductor-track/earth circuits, one of which contains a track break within the conductor span as shown on Fig. 9 is as follows:

$$Z'_{12:32} = -\frac{1}{2} k(1-\mu_3)(1-e^{-\gamma s_3})e^{-\gamma s} \{ (1-\mu_1)(1-e^{-\gamma s_1}) + e^{-\gamma(s_1-x)} [2\mu_1 + (1-\mu_1)\,(e^{-\gamma x} + e^{-\gamma(s_1-x)})]\} \qquad (19)$$

These impedances may be used in the propulsion cir-

cuit network diagram in problems involving a track break.

The second equation of (**16**) is the equation of voltage across the track break. With $I_2 = J$, that is, with zero earth current at the track generator point, $V_2 = (Z_{12} + Z_{22})\,J$, which is the voltage to be supplied by a perfect track booster transformer, that is, a transformer with zero exciting current. The voltage to be supplied by an actual transformer is a function of its exciting current, say $f\,(I_E)$, and

$$V_2 = Z_{12}J + Z_{22}I_2 = f\,(I_E) \qquad (\mathbf{20})$$

an equation of fundamental importance in the treatment of track booster transformers, since it is essential

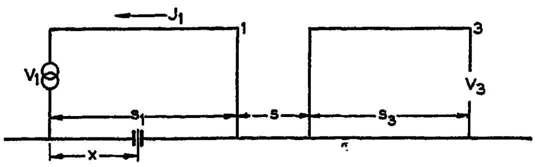


FIG. 9—MUTUAL IMPEDANCE OF CONDUCTOR—TRACK/EARTH CIRCUITS WITH TRACK BREAK

to finding the exciting current. With a unity ratio transformer, the exciting current is approximately equal to the earth current at the transformer point, that is $I_E = -\,I_2$, the impedance to flow of exciting current in the conductor winding usually being quite large. Although this equation cannot be solved formally without an explicit algebraic expression for $f\,(I_E)$ the solution may be carried out graphically or numerically when $f\,(I_E)$ is specified over a sufficient range.

The substitution $I_2 = I_2' - Z_{12}J/Z_{22}$ in equation (**16**) gives the equations in which the track generator current is superposed on the basic circuit; which are:

$$Z_{11}J + Z_{12}I_2' = V_1 \qquad (\mathbf{16a})$$
$$Z_{22}I_2' = V_2$$

where $Z_{11} = Z_{11}' - Z_{12}^2/Z_{22}$ = basic circuit self impedance. These equations show that the voltage of the track generator superposed on the basic circuit may be altered independently of the conductor current, and is thus at disposal to satisfy boundary conditions imposed by a discontinuity at a given point. This is a general result holding for more than one discontinuity of either kind and offers a convenient means of formulating the effects of a number of discontinuities; an example will be given in the case of two shunt discontinuities which follows.

Shunt Discontinuities

Fig. 10 shows two shunt discontinuities consisting of impedances Z_1 and Z_2 connected to ground at s_1 and s_2, respectively. The currents $2I_1$ and $2I_2$ which are to be superposed on the basic circuit are shown flowing from ground through the impedances Z_1 and Z_2, respectively, on to the track where they divide, half in each direction. On the track the currents are propagated exponentially. The equations determining these currents are the voltage equations at the two points, that is, the voltages between track and ground required by the currents I_1 and I_2 must be met by the voltages existing in the basic circuit. The equations are as follows:

$$-\frac{1}{2}kJ\,(1-\mu)\,(1-e^{-\gamma s})\,e^{-\gamma(s_1-s)} + kI_1 + kI_2e^{-\gamma(s_1+s_2)} = -\,2Z_1I_1 \qquad (\mathbf{21})$$

$$\frac{1}{2}kJ\,(1-\mu)\,(1-e^{-\gamma s})\,e^{-\gamma s_2} + kI_1e^{-\gamma(s_1+s_2)} + kI_2 = -\,2Z_2I_2$$

from which

$$I_1 = \frac{1}{2}kJ\,(1-\mu)\,(1-e^{-\gamma s})\,\frac{e^{-\gamma(s_1-s)}(2Z_2+k) + ke^{-\gamma(s_1+2s_2)}}{(2Z_1+k)\,(2Z_2+k) - k^2e^{-2\gamma(s_1+s_2)}} \qquad (\mathbf{22})$$

$$I_2 = -\,\frac{1}{2}kJ\,(1-\mu)\,(1-e^{-\gamma s})\,\frac{e^{-\gamma s_2}\,(2Z_1+k) + ke^{-\gamma(-s+2s_1+s_2)}}{(2Z_1+k)(2Z_2+k) - k^2e^{-2\gamma(s_1+s_2)}}$$

I_1 and $-\,I_2$ are opposite in direction to the basic track current between 0 and s, and so the average unit track current is:

$$\nu = \frac{\bar{I}}{J} = \mu + (1-\mu)\left(\frac{1-e^{-\gamma s}}{\gamma s}\right) - \frac{1-e^{-\gamma s}}{\gamma sJ}\,[e^{-\gamma(s_1-s)}\,I_1 - e^{-\gamma s_2}\,I_2] \qquad (\mathbf{23})$$

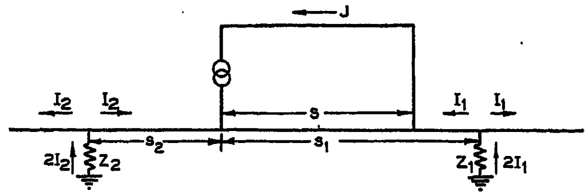


FIG. 10—CONDUCTOR—TRACK/EARTH CIRCUIT WITH TWO ARBITRARY IMPEDANCES CONNECTED TO GROUND OUTSIDE THE CONDUCTOR SPAN

In the limiting case $Z_1 = Z_2 = \infty$, both currents I_1 and I_2 vanish, as they should, leaving the basic circuit unaltered. In the limiting case $Z_1 = Z_2 = 0$:

$$I_1 = \frac{1}{2}J\,(1-\mu)\,(1-e^{-\gamma s})\,e^{-\gamma(s_1-s)}\;\frac{1+e^{-\gamma(s+2s_2)}}{1-e^{-2\gamma(s_1+s_2)}}$$

$$I_2 = -\,\frac{1}{2}J\,(1-\mu)\,(1-e^{-\gamma s})\,e^{-\gamma s_2}\;\frac{1+e^{-\gamma(-s+2s_1)}}{1-e^{-2\gamma(s_1+s_2)}}$$

The corresponding physical circuit consists of solid grounds at track terminals at s_1 and s_2, since the tracks beyond s_1 and s_2 where Z_1 and Z_2 are connected carry

no current and may be removed; this is apparent physically since the voltages to ground at s_1 and s_2 are reduced to zero, leaving no driving voltage for current beyond; it also follows from the identities

$$I_1 + I_2 e^{-\gamma(s_1+s_2)} = \frac{1}{2} J (1-\mu)(1-e^{-\gamma s}) e^{-\gamma(s_1-s)}$$

$$I_1 e^{-\gamma(s_1+s_2)} + I_2 = -\frac{1}{2} J (1-\mu)(1-e^{-\gamma s}) e^{-\gamma s_2}$$

which are equal and opposite to the basic circuit currents at s_1 and s_2, respectively, thereby canceling them, and therefore the currents beyond.

The integral track current between the limits $-\infty$ and $+\infty$ is $\mu s J$ as with the basic circuit since the superposed currents flow each way from points s_1 and s_2, just as the direct and reflected waves in the basic circuit. This holds also for the particular case $Z_1 = Z_2 = 0$ in which the tracks are terminated and solidly grounded at s_1 and s_2, as described above.

A further particular case of the general type of shunt discontinuity consists of track termination through arbitrary impedances, which may represent sections of track of arbitrary characteristic impedance and propagation constant as well as a single lumped impedance. This case may be derived from the case above by replacing the impedances Z_1 and Z_2 and the sections of track beyond them by a single impedance, which is their parallel impedance. Thus, the new impedances defined by

$$Z_1' = kZ_1/(Z_1 + k)$$
$$Z_2' = kZ_2/(Z_2 + k)$$

are the arbitrary terminal impedances at s_1 and s_2, respectively. The substitution required in equations (22), dropping subscripts, is

$$\frac{2Z + k}{k} = \frac{k + Z'}{k - Z'}$$

The limit $Z_1' = Z_2' = \infty$ gives the case of a track opened at s_1 and s_2 with the following results:

$$I_1 = -\frac{1}{2} J (1-\mu)(1-e^{-\gamma s}) e^{-\gamma(s_1-s)} \frac{1 - e^{-\gamma(s+2s_2)}}{1 - e^{-2\gamma(s_1+s_2)}} \tag{22a}$$

$$I_2 = \frac{1}{2} J (1-\mu)(1-e^{-\gamma s}) e^{-\gamma s_2} \frac{1 - e^{-\gamma(2s_1-s)}}{1 - e^{-2\gamma(s_1+s_2)}}$$

ACKNOWLEDGMENT

The writer's introduction to the subject came through a study of the early work of Messrs. A. E. Bowen and John R. Carson, and was extended during study of the theory of track and feeder booster transformers developed by Mr. Carson. The final systematization was made under the supervision of Mr. K. L. Maurer. Mr. Erling D. Sunde collaborated in the study of the basic circuit without discontinuities and contributed a number of important suggestions: the compact formula for circuit impedances and the introduction of the earth current parameters α and β are the results of his suggestions, and he and Mr. King E. Gould independently worked out the basic circuit cumulative induction curve in more detail than could be given here. Mr. Howard M. Trueblood first suggested the equation determining track booster transformer exciting current and his critical review of the present paper has resulted in a number of improvements.

Discussion

Keith L. Maurer: The peculiar feature of the type of circuit treated in Mr. Riordan's paper, which distinguishes it from the ordinary power circuit, is that one side is made up of a concentrated metallic conductor in parallel with a distributed conductor, the earth. The effect of the earth as a conductor upon the electrical constants of this type of circuit cannot be neglected as it ordinarily may be in the case of the usual power circuit. Examples of the distributed conductor circuit are the electric railway propulsion circuit discussed in the paper, power or communication circuits in cables with grounded metallic sheaths, and zero-sequence networks of power circuits with ground wires.

As mentioned in the paper, the applicability of transmission line theory to the railway propulsion circuit has been known for some time. However, relatively little use seems to have been made of the equations of propagation in practical work due, no doubt, to the fact that their straightforward application is complicated and laborious. The usual procedure has been to use simplified forms of the general equations obtained by assuming great circuit length. For example, the percentage division of current between the return system and earth for use in determining the self-impedance of a trolley-track circuit or the mutual impedance between such a circuit and exposed communication lines is ordinarily assumed to be independent of circuit length, and the value obtained from the infinite circuit length formula is used. This approximation may be sufficiently good for certain kinds of practical problems involving propulsion systems. Other types of problems, notably those involving the tracks by themselves, often require more detailed consideration of the distribution of current in the system.

The basic circuit treatment described by Mr. Riordan is a convenient method for handling problems of the latter kind. Much of the complication of the straightforward use of the equations of propagation is avoided since these equations are employed only to determine the properties of the basic circuit, after which the procedure is by superposition. The method has been found particularly convenient in studies of the design and performance of booster transformer systems; also in calculations of shielding from grounded cable sheaths in exposures to propulsion systems in which two-directional current feeds were involved. The property of the method which permits portions of a system to be studied apart from the whole, has been found convenient in coordination studies with electrifications yet in the design stage when frequent alterations are made as the design progresses.

With regard to experimental justification for the use of the equations of propagation for electric railway propulsion systems, tests both in this country and abroad have shown a degree of conformity which is perhaps surprising in view of the departures from smooth-line conditions which can be expected in the usual electrification. In a test made several years ago in this country on a four-track electrification the observed current differed from that calculated using smooth-line formulas by about 10 per cent in the current at any point, and by less than one per cent in the average current. In this case the energized overhead wire was eight miles long and the track was continuous for at least eight miles beyond the ends of the overhead wire.

The Boric Acid Fuse

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Synopsis.—Recognition of the part played by gas blasts in interrupting arcs in oil circuit breakers and expulsion fuses has opened new avenues for improvements in these devices. The present paper deals with a new type of fuse in which greatly improved performance is obtained by more effective use of the self-generated gas blast.

In this fuse a form of construction is used which permits the interruption of the smaller ranges of current within a device that is capable of interrupting also heavy short circuits up to 20,000 amperes or more. A special feature of this design is that the lower ranges of current are automatically transferred to, and interrupted in, a small auxiliary fuse bore.

While the construction may be used to advantage with any gas generating material, the present design embodies a compressed boric acid liner which has been found to be much more effective than fiber in extinguishing arcs.

Since boric acid evolves water vapor, a condensible gas, it becomes possible to construct a totally enclosed fuse in which the gas blast is discharged into a surface condenser. With such construction, currents of from 5 to 20,000 amperes at 13,000 volts have been interrupted with an electrode separation of less than six inches, using a relatively small condenser. Currents of more than 20,000 amperes have been interrupted by similar fuses of open type. This type of fuse may readily be designed for various current and voltage ratings.

* * * * *

I. Introduction

The value of gas blasts acting upon the electric arc, as a means of circuit interruption, has been well recognized for some time. Many investigators have shown that such blasts are extremely effective whether they originate from a high pressure source of gas or from the decomposition of insulating materials adjacent to the arc.[1,2] When it was recognized that such self-generated blasts play an important role in the operation of oil circuit breakers, new avenues were opened for improvements in this type of apparatus, the status of which had for many years remained substantially the same. This resulted in the development of the deion grid oil circuit breaker which by utilizing these gas blasts more effectively gives greatly superior performance when compared with conventional oil breakers.[3,4]

That the expulsion fuse is also dependent upon self-generated gas blasts is now well appreciated, many investigations having been made to determine the nature of these gas blasts as they apply in the extinction of arcs in fuses.[2,5,6] These investigations have quite naturally suggested ways and means by which devices of this kind might be improved.

The present paper deals with an improved type of expulsion fuse, the development of which is the outgrowth of these investigations. In this fuse the portions exposed to the arc consist of compressed boric acid which serves as the gas-generating material. In addition to this new gas-generating material the fuse employs a construction which differs radically from the conventional expulsion fuse. This construction utilizes more effectively the principles that have been found to apply in gas blast devices and may be used to advantage with any gas-generating material.

II. Effect of Form and Material on Characteristics of Expulsion Fuses

The principles governing the action of gas blast circuit interrupters have been treated quite fully in other publications,[5,1,2,6] and it is proposed to give herein only such a brief review of these characteristics as may be required to readily understand the present development.

The circuit volts per inch of fuse length, at a given current, that may be interrupted by an expulsion fuse are dependent upon the length and diameter of the fuse tube and also upon the material with which the arc comes in contact. Other factors remaining the same, lengthening the tube increases the volts per inch that may be interrupted, since the arc comes in contact with a greater length of tube, liberating more gas which, in turn, is effective throughout a greater length of arc. Similarly, decreasing the bore will increase the volts per inch that may be interrupted since the arc will be in more intimate contact with the tube, thereby causing a greater gas evolution as well as a more concentrated blast. A typical curve, showing how the circuit volts per inch interrupted vary with the tube diameter for one particular case, is shown in Fig. 1. This curve has been reproduced from the paper *The Expulsion Fuse*, by Slepian and Denault.[5]

The material, of which the fuse tube walls are composed, determines the magnitude and nature of the gas blast for given tube dimensions and arc current. Therefore, since the deionizing action upon the arc depends upon both the quantity and kind of gas in the blast, it is evident that the material of the fuse wall may further act to vary the volts per inch that may be interrupted. The material of the fuse wall will also determine the nature of the gases expelled into the atmosphere adjacent to the fuse. Organic materials, such as fiber, will liberate mainly hydrogen and carbon monoxide,

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1. For references see end of paper.

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both of which are inflammable and explosive as well as non-condensible. Such gases also have the property of remaining at low dielectric strength for appreciable lengths of time after expulsion from the fuse, and are, therefore, liable to cause breakdown between live parts in the vicinity of the arc. Gases evolved from inorganic materials may be non-inflammable, and in numerous cases possess the additional advantage that they may be condensed to liquid form, at moderate pressures, a property that can be utilized to great advantage in the construction of totally enclosed fuses. Experiments have further shown that arc gases from such of these materials as give off water vapor are much less liable to cause breakdown between adjacent live parts than gases evolved from organic materials.

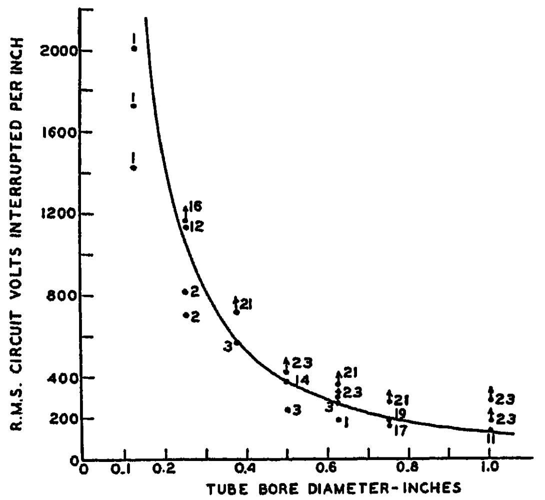


Fig. 1—Fiber Expulsion Fuse

Effect of varying tube diameter on the circuit volts interrupted at a constant current of 450 amperes. (Numbers indicate half cycles of arcing. Arrows indicate that backup breaker cleared the circuit)

Many inorganic materials have been tested to determine the effectiveness of their gas blasts when used in arc extinguishing devices. While several of these materials have been found to be comparable or superior to fiber, there is one, namely, boric acid whose arc extinguishing properties have been found to be outstanding. This material when used as an expulsion fuse liner will interrupt a much higher voltage than a horn fiber fuse of similar dimensions. Boric acid is readily compressed into hard, firm blocks of good mechanical strength that may be used to line fiber or other insulating fuse tubes.

A comparison of operating characteristics for horn fiber and boric acid fuse tube liners, using a plain expulsion fuse four inches in length and five-eighths inch internal diameter is shown in Fig. 2. These curves which are based on interruptions occurring in ten half-cycles or less, as explained in a previous paper,[5] show that under similar conditions the boric acid fuse is capable of interrupting 660 volts per inch, or more, over the entire current range, as compared to 400 volts per inch, or more, for a fiber fuse.

This set of curves illustrates further the typical voltage-current characteristic of gas blast devices. For very small currents a high voltage can be interrupted since the arc is of very small cross-section and is quickly deionized at a current zero. For somewhat larger currents the arc section increases, yet does not completely fill the tube, so as to produce a vigorous gas blast. The rate of deionization at a current zero is, therefore, much slower than for the smaller currents, thereby creating a range of currents, the value depending mainly upon the diameter of the tube, at which the voltage that can be interrupted decreases and reaches a minimum. Beyond this range the gas blast becomes more and more intense and the voltage that can be interrupted rises very rapidly with increasing current.

III. A New Fuse Design Utilizing the Gas Blast More Effectively

To employ to greater advantage the characteristics of gas blast devices as discussed above in Section II, a particular form of fuse has been designed which is radically different from any previous fuse construction. A sectional view of this fuse is shown in Fig. 3. Essentially, this consists of a short fusible element that links the lower stationary electrode to a spring actuated movable plunger, which upon melting of the fusible element is withdrawn through the boric acid tube. In order to extinguish the lower ranges of current the main fuse bore has been made as small as possible, the cross-section of the hole being only sufficient to provide proper clearance for the plunger designed to carry rated current without appreciable heating. The fusible element, instead of extending throughout the whole length of the fuse tube, is located at one end of the tube and is relatively short. This end of the tube has a bell shaped opening in which the arc is initiated when the fusible section melts. If the current happens to be extremely large it will generate a sufficient gas blast even

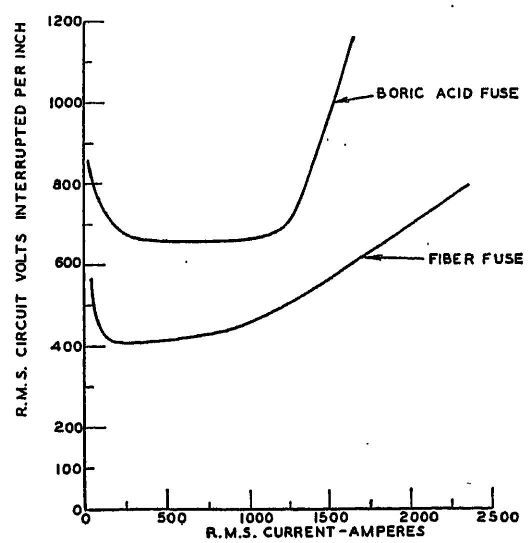


Fig. 2—Comparison of Boric Acid and Fiber Fuses

in this enlarged opening to interrupt the circuit at the end of the first half-cycle of arcing. The large diameter of opening together with the short length of arc insures that there will be no excessive pressures, even with extremely high currents. Smaller current arcs which are not interrupted in the first half-cycle in the enlarged portion of the fuse bore are lengthened and drawn into the more restricted sections of the tube by the receding plunger, thus increasing the gas blast until extinction occurs. With this construction, therefore, it is possible to clear the full range of currents in a single tube, without developing excessive pressures on the higher currents or going to impractical lengths to clear the lower ranges of current. However, for currents below six or seven hundred amperes, a hole much smaller even than the main fuse bore would be preferable. It was recognized that if a hole smaller than that required for the main conductor were used to extinguish currents in the above range, the total fuse length could be appreciably shortened. This feature has actually been accomplished by the addition of an auxiliary fuse wire in a small hole

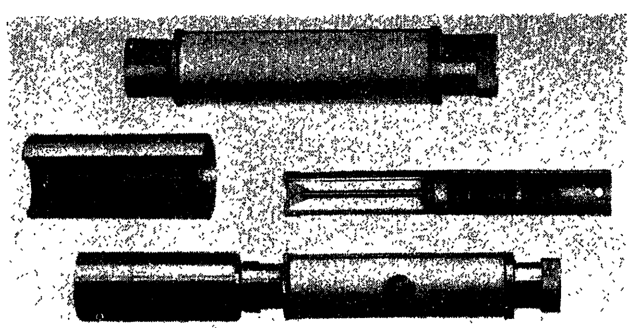


Fig. 3—Views of Boric Acid Fuse

through the boric acid, parallel to the main fuse bore. The conductor in the small hole is rigidly attached to the electrode at the spring end of the fuse, while at the bell end of the fuse it terminates in a washer adjacent to, but insulated from, the main electrode. This conductor, therefore, carries no current whatsoever until after the main fuse element has melted and established an arc. The arc is then in parallel with the short gap of insulation that separates the terminal washer of the small fuse from the adjacent electrode, and since the space between the electrode and washer is highly ionized, it breaks down at once, placing the small fuse wire in parallel with the arc in the main hole. What happens at this point is a function of the arc current, the thermal capacity of the auxiliary fuse wire, and the rate at which the plunger is withdrawn. For currents that require one or more half-cycles to melt the auxiliary fuse wire, the parallel arc in the main fuse bore is extinguished at once, since it is shunted by the low resistance auxiliary fuse. The current is, therefore, transferred to, and interrupted by the auxiliary fuse, the plunger having been withdrawn by this time to such a point that an arc will not restrike to it. For somewhat larger currents that melt the auxiliary fuse in a half-cycle or less, the main arc is extinguished for a fraction of a half-cycle but, due to the high arc voltage at the end of the first half-cycle when the arc is extinguished in the small hole, it restrikes to the movable plunger which in this time has traveled only a very short distance. The current is then interrupted as the plunger is withdrawn into the main fuse bore. For large currents the IR drop over the small fuse is sufficient actually to maintain an arc in the main fuse chamber, the current being divided between the two paths. The small fuse melts almost instantly, the arc voltage is insufficient to maintain an arc in the small hole and all the current transfers to the arc in the main bore, where it is interrupted at a following current zero as previously explained.

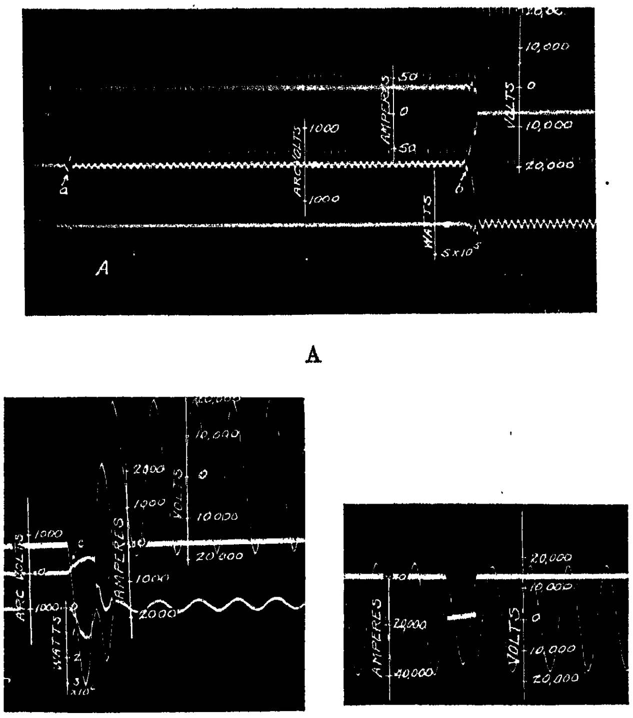
It is evident that this arrangement is capable of handling the complete current range, and that the length of the fuse need be only sufficient that the lower current interrupting capacity of the main fuse bore overlaps sufficiently the upper current capacity of the auxiliary bore. The upper limit of the current to be interrupted by the auxiliary fuse bore is determined by the thermal capacity of the fuse wire in it, and may thus be regulated, within limits, at will. Occasions may arise in which it is necessary to interrupt currents so small that they will not melt the auxiliary fuse. To insure the opening of the circuit under these conditions, the auxiliary fuse wire is attached to the movable plunger in such a manner that after the plunger has receded about half way into the main fuse bore the auxiliary fuse wire is mechanically withdrawn into the auxiliary fuse bore where the resultant arc is readily extinguished. This withdrawal can occur only after such time has elapsed that the proper selection of path for the interruption of the current has been determined as previously described, and in no way affects the operation of the fuse throughout the higher ranges of current.

The three oscillograms reproduced in Fig. 4 show how this fuse operates on small, medium and large currents. In oscillogram 4A for a small current the first drop in arc voltage occurs at the time when the gap between the auxiliary fuse terminal washer and the adjacent electrode is bridged by an arc, causing simultaneously the extinction of the arc in the main fuse chamber. This change in arc voltage is shown at point a in the magnified arc voltage record of element No. 3. The smaller arc voltage which follows, is that of a short arc from the adjacent electrode to the terminal washer of the auxiliary fuse. In this particular test the auxiliary fuse wire was not mechanically withdrawn and hence a large number of half-cycles elapsed before the small fuse melted. When this occurred the arc voltage rose as seen at point b, and the current was extinguished. Oscillogram 4B shows a case of intermediate current value where the arc transfers to the auxiliary hole, is extinguished there, as indicated by the high arc voltage at point c, and then restrikes again in the main fuse bore, where it is extinguished as it is drawn into the

main fuse bore by the moving plunger. Oscillogram 4C shows the extinction of a heavy current arc. Here there is no evidence of any high arc voltage to indicate that the arc at any time was completely transferred to the small hole. The main arc in this case undoubtedly continued to carry current even while a portion of the total current sufficient to melt the auxiliary fuse was shunted through the auxiliary path.

IV. Totally Enclosed Fuses

The fact that the gas blast in the boric acid fuse consists of water vapor, a condensible gas, makes it possible to build a totally enclosed fuse of high interrupting capacity. With fiber fuses such construction is impractical on account of the enormous pressures that would be developed by the permanent gases liberated during the arcing period.



A

B C

Fig. 4

When boric acid is used as the gas producing medium, the water vapor emerging from the fuse may be discharged into a closed surface condenser of metal tubes or plates. Such a condenser serves to absorb heat energy from the gas, which causes it to condense, and thus eliminates excessive pressures within the closed fuse structure. A condenser of this kind is shown in the sectioned fuse of Fig. 3.

Tests on condensers of this type show that about 80 per cent of the total arc energy can be accounted for as temperature rise in the condenser. The remainder of the energy is used in heating other parts of the fuse, and in supplying the energy required for chemical decomposition of the boric acid. In an actual test at 4,000 amperes, the oscillogram shows 57.5 kilowatt-seconds of arc energy, equivalent to 13,700 calories. The condenser, which weighed 3,060 grams, was raised in temperature 40 deg. cent. This represents a heat input of approximately 11,650 calories, or 85 per cent of the arc energy. That a large percentage of this energy is actually absorbed by the condenser during the arcing period is indicated by the fact that a condenser consisting of 2,120 grams of copper plates housed in a 1,500 gram brass case operates satisfactorily at currents of 12,000 to 20,000 amperes. On these operations the arc lasted for one to two half-cycles, and the energy measured from the films in several instances was in excess of 200 kilowatt seconds corresponding to 48,000 calories. Calculations readily show that if this energy were expended in generating uncondensed steam within the available fuse volume of less than 1,000 cubic centimeters, pressures would be developed far in excess of those required to rupture the fuse case. Evidently a large percentage of the energy must have been absorbed by the condenser during the arcing period. These actual test results, furthermore, agree with calculations of heat flow, which show that if copper condenser plates less than 3/64 inch thick have constant temperature maintained at the plate surface, more than half of the total heat capacity of the plate at the surface temperature will have been absorbed in the first half-cycle of a 60-cycle arc. The rapid absorption of arc energy by the condenser is further augmented by the extremely high superheat at which the arc gases impinge on the condensing surfaces as well as by the increase in pressure which permits condensation to occur at higher temperatures.

This totally enclosed fuse has several advantages, the most obvious being freedom from expelled flame and ionized arc gases. The condenser also renders the operation of the fuse noiseless. Even at the maximum currents the fuse produces no audible sound other than that caused by the mechanical operation of the plunger.

V. Test Results

At the time of writing only laboratory tests had been made on the new boric acid fuses. These tests are, however, rather complete, and have been made on circuits with an extremely rapid rise of recovery voltage after current zero, and which are therefore more difficult to interrupt than any circuit likely to be met in service. In all tests the current was limited by the transformer or machine reactance only, or by additional air-core reactance, except for the currents below 400 amperes which were limited by an iron-core reactor, thus giving the most unfavorable conditions possible for interruption of the circuit.

These tests show that with a circuit e.m.f. of 13,800 r.m.s. volts, the fuse is capable of clearing the full current range up to 20,000 amperes using a 6-inch long boric acid filler. In this filler the main fuse bore is large enough to accommodate a 5/16-inch plunger, and the

auxiliary fuse hole is about 0.1 inch in diameter. Operating characteristics for a fuse of this kind are shown in Fig. 5. There are two distinct curves, the first representing extinctions occurring in the auxiliary fuse bore, and the second representing extinctions in the main fuse bore. It may be seen that, in this particular design, currents up to about 600 amperes are cleared by the auxiliary fuse, while above this value the arc restrikes and is cleared in the main fuse chamber.

In Fig. 6 is shown an oscillogram of an operation of a totally enclosed fuse of this type at 20,000 r.m.s. amperes, 12,000 r.m.s. restored volts. The circuit was interrupted with one half-cycle of arcing. The average arc voltage was approximately 1,350 volts, and the arc energy was calculated to be approximately 300 kilowatt-seconds.

Fig. 7 shows an operation with a similar fuse of open type. The current in this test on the first half-cycle measures 20,300 r.m.s. amperes, and the restored voltage, 11,800 r.m.s. volts. The interruption occurred in one half-cycle.

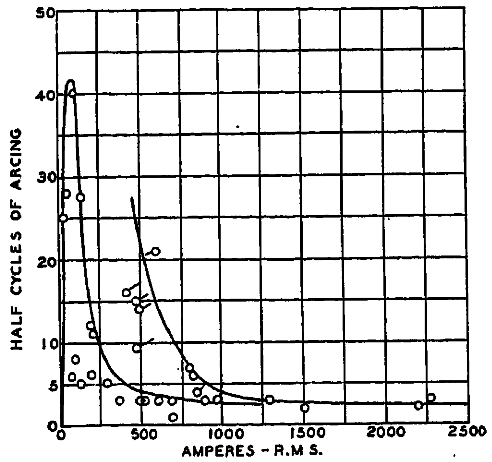


Fig. 5—Performance of Experimental Plunger Type Boric Acid Fuse at 13,800 R.M.S. Volts, 60 Cycles with Maximum Electrode Separation of 6 Inches

VI. Summary and Conclusions

Over 500 tests on plunger type boric acid fuses, made at voltages up to 14,000 r.m.s. volts and currents ranging from 5 to 20,000 amperes show not only that boric acid produces a far more effective and safe gas blast than organic insulation, but also that the particular type of construction employed in this design utilizes the gas blast to better advantage than the conventional expulsion fuse.

By using an auxiliary fuse bore to clear the smaller currents it has been possible to interrupt over 2,000 volts per inch of fuse length throughout the entire current range from 5 to 20,000 amperes. These principles may readily be incorporated in fuses with voltage ratings other than the one described in this paper by appropriate changes in design.

With boric acid as the gas-producing medium in fuses of this type, water vapor is evolved, which permits the construction of a totally enclosed high-capacity fuse. This is accomplished by using a surface condenser to recondense the water vapor, thereby eliminating excessive pressures within the closed fuse structure. This condenser serves not only to prevent escape of flame, but also acts as an excellent muffler.

A fuse embodying the principles which have been discussed in this paper lends itself well to a construction

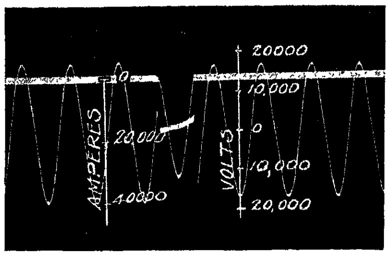


Fig. 6

in which the various fuse parts are so assembled that those portions affected by the arc form a separate unit or renewable filler which may easily be replaced. A design incorporating such features is illustrated in Fig. 3.

It is evident that the fundamental principles governing the operation of this fuse are in no way dependent upon the use of a condenser which renders the fuse totally enclosed. The excellent current interrupting performance obtained with the materials and construction as embodied in this design may thus readily be

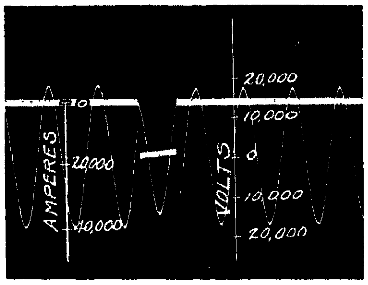


Fig. 7

secured, both in those cases where the totally enclosed feature is desirable and in the larger field where a less expensive open type of fuse is sufficient. Furthermore, a fuse such as described in this paper should open new fields in the application of high-voltage fuses.

Acknowledgment

The authors wish to acknowledge their indebtedness to Dr. Slepian and Mr. C. L. Denault for the valuable suggestions they have given, and to Mr. J. W. Huffstutter and Mr. C. J. Witsberger, who have cooperated

in obtaining much of the experimental data used in the preparation of this paper.

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Discussion

T. G. LeClair: The new fuse described in this paper has one feature of material value, *viz.*, the lack of an inflammable liquid filler. This characteristic is a very excellent safety recommendation.

The illustrations do not give a complete picture of the fuse and it is difficult to see whether the inclosed type has any opening for the escape of gases if the internal pressure should increase unexpectedly. I should like to ask the authors if they could tell us from the series of tests performed what takes place when the fuse is called upon to interrupt a current beyond its capacity. In other words, what is the effect of failure? With the inclosed type fuse, does the fuse structure merely burn, under the influence of the arc, or does the sudden increase in gas pressure cause an explosion which scatters the various parts of the fuse?

G. F. Lincks: In reviewing the paper, there are several points which are not entirely clear.

The authors indicate the arc-extinguishing benefits obtained by the use of boric acid, describing the initiation of the arc as being at the open or large chamber end of the tube. Experience with expulsion type fuses using fiber fuse holders, indicates that a much higher interrupting capacity is obtained with this positioning of the fuse links. Is it not possible that the location of the fuse link in the new design is largely responsible for the successful operation at the high currents?

While the paper states that over 500 laboratory tests were made at voltages up to 14,000 and at currents ranging from 5 to 20,000 r.m.s. amperes, it does not specifically cover the combinations of voltage and interrupted current nor does it mention the actual sizes of fuse links used in the tests. The oscillogram in Fig. 4A with the attendant description apparently shows the operation of a main fuse element having a very low current rating, since it was blown by 50 amperes peak current and the plunger drawn away sufficiently to permit arc-over to the auxiliary fuse wire in approximately 3 cycles (0.05 second). In our investigations under somewhat similar conditions, we have found that the use of fuse links of the higher current ratings brings in different and in some ways, more difficult, problems. Will the authors kindly give more detailed information as regards the combinations of the voltage, the interrupted current and the rating of the fuse links used in the tests upon which the reported successful operation is based?

Comparison of the times required to melt the main and the auxiliary fuse elements on the same oscillogram (Fig. 4A) indicates that the auxiliary fuse wire was considerably larger than the main fuse element. Is this necessary for all fuse ratings? If so, how is this to be taken care of without increasing the 0.1 inch auxiliary fuse bore for the larger ratings, which would affect the operating ability at the low currents?

In the description of the operation of the fuse, no mention is made of the effect on the condenser plates of the expelled hot gases, vaporized fuse metal, and decomposed boric acid. Investigation under somewhat similar conditions indicates destructive temperatures and "schooping" of molten materials in the arc gases, especially with the larger fuse links. In the laboratory tests mentioned in the paper, was there any tendency for the hot gases to burn or "schoop" insulating oxides or boric acid on to the condenser plates which would lower the efficiency of the condenser, required to effect rapid condensation?

In the normal operation of a fuse the effect of time under varying atmospheric conditions is important to avoid unnecessary fuse operation. This is particularly true if the fuse element is at the open end of a fuse holder and thus more or less directly exposed to the weather. In the design described what protection is afforded the fuse link and boric acid liner on the open end fuse when the condenser is omitted and how will any means for doing this affect the reported successful results?

One of the important operating requirements of a fuse is that after the fuse link has blown the circuit should be open with no permissible leakage current at rated voltage. The advantages claimed for use of boric acid are premised on its ability to contain and give off more moisture than fiber, thereby permitting shorter spacing between electrodes. What information is available as to the effect of the greater amount of moisture in the compressed boric acid and the shorter spacings on leakage after the circuit has apparently cleared?

Speed of operation is an important requisite of fuse links since it limits the time settings on circuit breaker relays all the way back to the generating station. No mention is made of the time-current characteristics in the paper although referring again to oscillogram Fig. 4A and the description, it would appear that the movement of the plunger is somehow retarded, since it did not mechanically break the auxiliary fuse link in less than approximately one second. It is stated that this should occur when the plunger has traveled one-half the normal movement. How do the time-current characteristics of the boric acid fuse compare with those of relays and other modern fuse links?

H. L. Rawlins: Mr. LeClair raises the question as to what will happen to the totally enclosed fuse if it is called upon to interrupt a current beyond its capacity. Obviously the pressure generated will cause the fuse structure to burst at its weakest point. If the condenser is solidly constructed, this will result in the bursting of the fiber retaining walls and other light parts. It is, then, evidently practical to design the condenser with a weakened section such that if failure does occur the pressure will be released without scattering the various parts of the fuse.

However, if the fuse is properly applied, there will be no failure, for repeated tests at 13,200 volts at currents up to 20,000 amperes have been made without failure of the totally inclosed fuse. At the present time all operating companies know on what parts of their system short circuits in excess of 20,000 amperes will be encountered.

Mr. Lincks raises a number of questions which are taken up in order in the following:

The location of the fusible section at the belled end of the fuse is responsible for a large increase in the interrupting ability of the fuse since it permits the extinction of the heavy currents in a large, freely vented bore.

All tests on the 15,000-volt fuse, as described in this paper, were made at 13,200 volts or more at all currents up to 20,000 amperes.

For convenience in testing most of the lower current tests described were made on fuse elements of lower ratings while most of the higher current tests were made on fuse elements of higher rating. However, the actual fusible section in this fuse is so short that in all cases the arcing is between the moving copper plunger and the lower electrode. It has been determined that the amount of material in this extremely short gap has no influence upon the proper functioning of the fuse.

The size of wire used in the auxiliary fuse bore is independent of the rating of the fuse and is determined so that blowing time on higher currents will be such that reignition and extinction of the arc will occur in the main fuse bore, while on lower currents the blowing time will be long enough to prevent reignition in the main bore, thereby insuring that the lower currents will be interrupted in the auxiliary fuse bore. This means, of course, that the same size of auxiliary fuse wire will be used for all of the current ratings.

In the totally enclosed fuse there is some condensation of the oxide upon the condenser plates and it would seem that upon repeated operation of the fuse, the effectiveness of the condenser plates would be decreased. However, repeated tests have been made using one set of condenser plates without apparently decreasing their effectiveness. This is probably due to the fact that condensation occurs at temperatures above the melting point of boric oxide due to the high pressure at which condensation occurs.

When the fuse is used without a condenser the open end of the fuse is tightly sealed by means of a thin disk to prevent exposure to the atmosphere of the boric acid. Upon operation of the fuse this disk is blown clear.

After operation of the fuse the boric acid remains in a dry state. The boric acid in such a state has leakage characteristics equally good and in some respects better than fiber. Due to its being an inorganic material it will not carbonize and form leakage paths as is the case with fiber. Therefore, the length of time at which voltage is left on the blown fuse has no effect upon breakdown along the boric acid surface. This has been verified by prolonged voltage tests on blown fuses.

The test shown on oscillogram 4A was made upon a fuse without the mechanical pullout feature. Therefore, the time of current flow through the auxiliary fuse wire represents the time to blow the auxiliary fuse wire. This oscillogram brings out very clearly the action of the auxiliary fuse wire in shunting the lower currents away from the main fuse bore. The mechanical pullout feature was adopted to reduce this time of current flow after blowing the main fuse link and in no way affects the selective action of the auxiliary fuse wire in shunting low currents to the auxiliary fuse bore.

Due to the short section of low melting point fusible material used as the fuse element in this fuse, the time characteristics on blowing will be very fast and will line up with the time characteristics of other modern fuse links.

The Torque Balance Telemeter

BY A. J. JOHNSTON[1]
Associate, A.I.E.E.

THE word telemeter, to the electrical industry, has become the name of a complete measuring, transmitting, and receiving apparatus for indicating, recording, or integrating at a distance by electrical translating means the value of a quantity.

The ideal telemeter should consist of apparatus capable of indicating or recording accurately and instantaneously, the value of the quantity being measured. It should require a minimum amount of energy from the source being measured and should not require a closely regulated auxiliary power supply. It should also be flexible, easy to install, and easy to maintain. That high-speed response and high degree of accuracy are considered very important, is shown by the following statement of the committee on automatic stations in its 1931 annual report on telemetering:

> One point emphasized was the lack of high-speed response with accuracy comparable to the usual line of switchboard indicating instruments. There is a tendency, where high speed is desired, to sacrifice somewhat the matter of accuracy.

Telemeters in the past have not been capable of instrument speed and accuracy, partially because engineers looked with disfavor on telemeters which employed electron tubes, even though the use of tubes may have greatly increased the rapidity of response. This, no doubt, was due in part to the fact that tubes change their characteristics with usage. Another reason was a belief that open line wires would most generally be used for telemetering purposes. Thus, if telemeters were to have wide application and be independent of line leakage and induced voltage, they must be of the impulse type. The indicating or recording apparatus of an impulse type telemeter must be heavily damped, and is, therefore, slow to respond.

The annual report of the American Telephone and Telegraph Company shows that approximately 94 per cent of the total telephone wire mileage in the United States is now in lead-sheath cable. It also shows that the open-line wire mileage has decreased approximately 40 per cent since 1925. This, together with the fact that the telephone companies have cooperated with the operating companies in leasing channels for telemetering purposes, at a very reasonable rate, has had the double effect of making available conductors which have very high leakage resistance, are practically free from induced voltages, and at the same time has relieved the operating companies of the initial cost of installing such conductors.

It is now possible, by means of the torque balance telemeter, to indicate or record, up to a distance of one hundred miles, the value of such quantities as watts, amperes, volts, temperature, pressure and flow with instrument speed and accuracy. The value of direct current which is used as the translating means of the telemeter is well within the limits of voltage, current and noise-units stipulated by the telephone companies. The telemeter automatically compensates for variation in line wire resistance, auxiliary supply power voltage, and variation in tube characteristics. In general the torque balance telemeter approaches, in almost all respects, the requirements of the ideal telemeter.

Description

The receiving and indicating apparatus of the torque balance telemeter is one and the same device and will hereafter be referred to as the receiver. Likewise the measuring and transmitting apparatus is a single unit and will be referred to as the transmitter. The measuring element may be one of two general classes, depending upon the quantity to be measured. Pressure gages and selsyn motors are classed as the position type, and voltmeters, ammeters, and wattmeters, are classed as the torque type. Of these only the wattmeter will be discussed in detail in this paper.

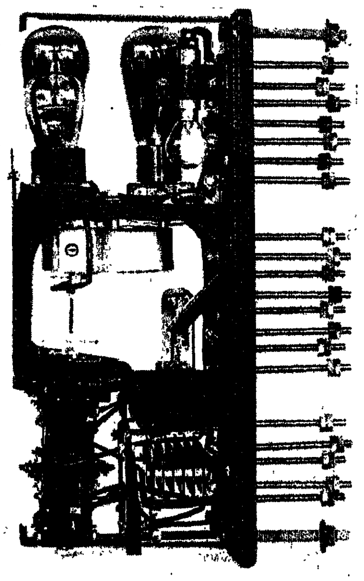

Fig. 1—Transmitter for Measuring Positive and Negative Watts

The *receiver* may be any form of indicating or recording d-c. milliammeter. If desired two or more receivers may be operated in series by one transmitter. Likewise, when it is desired to totalize the values of two or more quantities, the transmitters may be connected in parallel to a single receiver.

The *transmitter*, shown in Fig. 1, is composed of four

1. General Electric Co., Philadelphia, Pa.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

major parts; the measuring or operating element, the balancing or restraining element, the universal coupling, and the electron tube circuit. The apparatus, with the exception of the auxiliary power transformer and condenser, is contained in a standard 5½-in. by 16-in. case. The tubes and instrument parts are mounted on a cast bracket.

The *operating element* shown in Fig. 1, is a standard indicating wattmeter, except the control springs, pointer and damping disk are removed, and a yoke is fastened to the shaft of the element to provide a means of coupling it to the shaft of the restraining element. Lead-in spirals are provided to supply electrical connections to the moving coils.

The *restraining element* in all cases is a standard permanent-magnet d-c. milliammeter except the control springs are replaced by lead-in spirals, and the pointer is replaced by a pin to provide a coupling to the operating element.

The *connecting yoke*, upon which an instrument mirror is mounted, is supported at the top by means of the pin which is fastened to the shaft of the restraining element, being free to move about the axis of the pin. The bottom prongs of the connecting yoke hang free through a loop of silk thread supported by prongs of a second yoke which is fastened to the shaft of the operating element. Thus a flexible insulated universal coupling is formed between the two elements. The total weight of the connecting yoke and mirror is 1.25 grams.

The *electron tube circuit* consists of a pliotron, two photoelectric tubes, and an auxiliary power supply transformer. The photoelectric tubes, which are of the gas filled type, are connected in series across one secondary winding of the transformer with their common junction connected to the grid of the pliotron. The plate of the pliotron is connected to a second secondary winding of the transformer through the restraining element and receiver. Two other secondary windings supply voltage to the filament of the pliotron and lamp.

The pliotron filament, which is of the thoriated tungsten type, is rated at 7.5 volts and the plate current is rated at 28 milliamperes. However, the transmitter is designed to operate the filament at 6.5 volts and to require not more than 10 milliamperes from the plate. The photo tubes are also operated below their normal rating of 20 microamperes. Approximately six microamperes circulate in this circuit. Likewise the lamp bulb is operated at 3.9 instead of 6 volts. This insures a life of approximately one year for the tubes and lamp. The total auxiliary power consumed by the telemeter is approximately 40 watts.

Operation

The operation of the telemeter may be best explained by first examining the circuits shown in Fig. 2.

The *fundamental circuit* consists of an operating element, restraining element and a receiver. The receiver is a standard d-c. milliammeter. For purposes of discussion it will be assumed that the rheostat, which is operated by the common shaft of the operating and restraining elements, is frictionless, has a resistance range from zero to infinity, and requires an armature movement of two degrees to cover the complete range. The restraining element is connected in series with the receiver and the rheostat to a direct-current source. The potential is so chosen that the restraining element torque is in opposition to the operating element torque. Since the control springs are removed from both elements, the restraining element torque is the only force opposing the movement of the operating element. Such a circuit is completely self-compensating for changes in potential of the direct-current source and resistance changes of the line wires, because the torque of both elements must always be equal and opposite. Any change in the circuit destroying this balance would

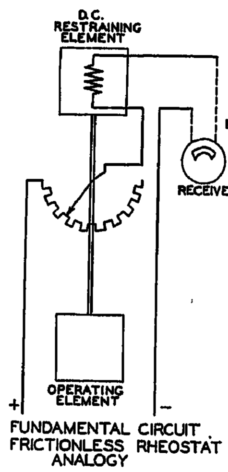

Fig. 2

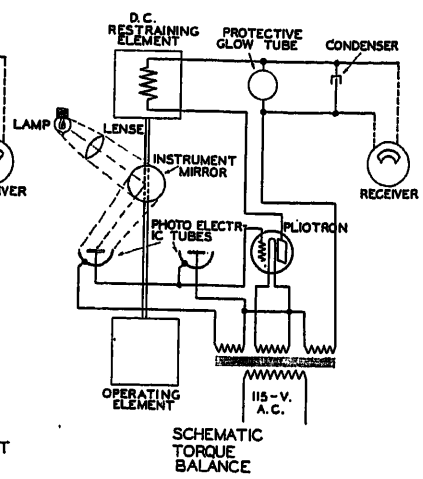

Fig. 3

cause a movement of the shaft and rheostat armature in the proper direction to reestablish the balance. From the foregoing it will be seen that there is no definite position of the moving system for a given measured quantity. Thus, neglecting bearing friction and line leakage, the deflection of the receiver is a true measure of the quantity being measured by the operating element.

The *photoelectric circuit and optical system* of the torque balance telemeter shown in Fig. 3 are used as a means of maintaining a balance between the two elements instead of the frictionless rheostat. The optical system is so arranged that light from the lamp source is condensed by a 25 diopter plano-convex lens on a stationary mirror which reflects it to the instrument mirror mounted on the connecting yoke, and thence to the photoelectric tubes. The photoelectric tubes are placed so that the beam of light may fall entirely on either tube or may fall partially on both tubes. The constants of the circuits are such that when light is falling only on the left hand photoelectric tube the grid potential is increased sufficiently to bias the pliotron to cut-off, in other words, the pliotron has infinite resistance. When

all of the light is falling on the right hand photoelectric tube the grid potential of the pliotron is reduced to a point where the plate resistance is approximately 10,000 ohms, thereby permitting a plate current of more than 10 milliamperes through a total external loop resistance of 8,800 ohms. When the light beam falls anywhere between these two extremes the pliotron resistance accordingly will be somewhere between the extremes of 10,000 ohms and infinity. Thus, since the light beam has no inertia the optical system and electron circuit form a frictionless rheostat.

When the telemeter is used with external resistance less than 3,500 ohms, the transformer is used to supply power directly to the tubes. In this case the translating means is half-wave rectified alternating current. A condenser is connected across the line wires at the transmitter to smooth out the wave.

When the external resistance is more than 3,500 ohms full-wave, copper oxide rectifiers are inserted to supply direct current to both the plate and grid circuits of the pliotron. This addition is made to reduce the peak values of the voltage impressed on the line wires.

Characteristics

Of primary importance in the design of any electron-tube circuit for use with measuring apparatus, is self-compensation for changes in tube characteristics. The circuit shown in Fig. 3 is not only compensated for changes in tube characteristics, but also for changes in auxiliary power supply voltages and line wire resistance.

Variation in auxiliary supply voltage affects the current output of the electron tubes as well as the illumination of the lamp. If the voltage is reduced there will be a reduction in the torque of the restraining element which will cause a movement of the shaft in the direction of the torque of the operating element. This movement will increase the light on the right hand photoelectric tube. The shaft will take up a new position at a point where the increased light on the right hand photoelectric tube will sufficiently reduce the grid bias on the pliotron to allow it to pass the original value of current. The action is of course reversed when the supply power voltage is increased.

Changes in electron tube characteristics will occur very gradually. However, the compensation for this change is accomplished in exactly the same way as for changes in supply power voltage. As long as the electron tubes are capable of passing sufficient current to balance the restraining element against the full load torque of the operating element and to prevent any current from flowing when there is no power in the operating element the tubes are satisfactory for service.

Changes in line wire resistance are compensated for in the same manner. The shift of the light on the photoelectric tubes has the effect of changing the pliotron plate resistance by an amount equal and opposite to the change in line wire resistance.

Changes in illumination due to dust on the lens and mirrors or to deterioration of the lamp filament are fully compensated for as long as enough light strikes the photoelectric tubes to give them control of the pliotron. The commercial models will usually operate considerably less than 50 per cent normal illumination.

The *sensitivity and responsiveness* of the telemeter is comparable to that of the usual line of switchboard instruments. Field tests have shown that the transmitter and receiver together actually respond more quickly than an indicating wattmeter connected directly to the measured source in spite of the fact that the responsiveness of the receiver is in the order of two

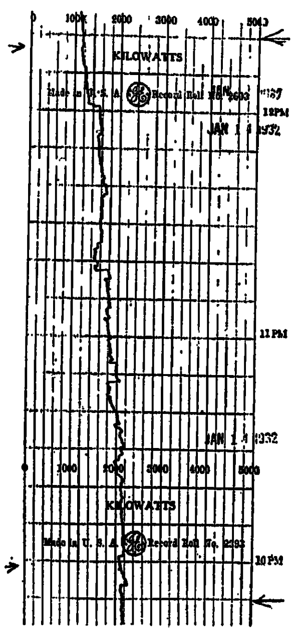

Fig. 4—Chart from Type C-4 Recording Wattmeter Multiply Scale Reading by 1.5

seconds while the responsiveness of the indicating wattmeter is in the order of 1.5 seconds. This can be explained by the fact that there is no damping in the transmitter circuits, and that the moving system has to move not more than three degrees to cause a change in the line current from zero to maximum. Laboratory tests show that the line current reaches a maximum value, which is in the order of twice full-scale current, approximately one-tenth second after full scale power is suddenly applied to the operating element and that the line current is settled down to a steady value within one second. Thus, the receiver is accelerated rapidly during the first half second.

The charts shown in Figs. 4 and 5 were taken in field test and show conclusively that the receiver was capable of recording any changes that could be recorded by the local wattmeter.

The *accuracy* of the transmitter is usually given the same as a standard switchboard type indicating instrument; *i. e.*, 1 per cent of full scale. By examination of Fig. 3 it can be seen that the complete telemeter is theoretically capable of very high degrees of accuracy.

This is especially true when the receiver is calibrated with the transmitter, because the receiver scale can be marked directly in terms of the values of power in the measured source.

The scale of the receiver is directly proportional and is therefore more easily read than the scale of a standard wattmeter. It will be recalled that the moving system of the transmitter has a maximum deflection of approximately two degrees and that the current field of a wattmeter is practically uniform over that range. Thus the torque produced by the operating element is directly proportional to the watts in the measured source.

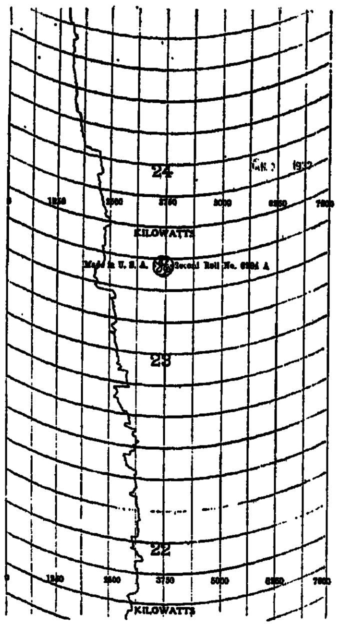

Fig. 5—Chart from Type C-19 Recorder Operating as the Receiver for a Torque Balance Telemeter Transmitter

Connected to the same source as the C-4 recording wattmeter shown in Fig. 4

This feature is very important because it allows the telemeter to be readily used for totalizing alternating-current watts or any other quantity which will produce a torque in the operating element directly proportional to the measured quantity. Some operating elements, such as a-c. ammeters, do not have a direct proportion between current and torque even though the shaft is allowed to turn through only a narrow range.

The factors which are most likely to affect the accuracy of the telemeter are line leakage, bearing friction, and balance of the transmitter moving system.

Line leakage is in effect a shunt across the receiver. If the leakage resistance is constant, it can be compensated for by calibration, but if the leakage resistance is variable the percentage error introduced will be directly proportional to the percentage of current shunted from the receiver. Line leakage can be expressed in general as directly proportional to length of line and inversely proportional to leakage resistance. The calculated error due to leakage in 100 miles of No. 19 B. & S. gage lead-sheath cable is less than one-tenth of one per cent. The calculated error for 100 miles of No. 8 B. & S. gage open line wires is less than five per cent when the receiver is an indicating instrument. This calculation is based on wet weather conditions estimated to occur one day out of one hundred. During dry weather the error is negligible.

Bearing friction is present in any type of instrument, and since the transmitter is composed of standard instrument parts it has no more effect than in standard indicating instruments.

Proper balance of the transmitter moving system is very important if the telemeter is to be perfectly self-compensating. It must be free to move throughout its entire range so that the current in the restraining element will be exactly the same for balancing a given torque of the operating element regardless of the position of the moving system. No trouble of obtaining a satisfactory balance has been experienced in the commercial models.

Application of Various Types of Transmitters

The foregoing discussion applied only to the transmitter for measuring single-direction watts. When it is desired to measure directional quantity, such as positive and negative watts, a second pliotron is added to the transmitter in such a way as to make the circuit function as a frictionless voltage divider instead of a frictionless rheostat, so that positive and negative values of current can be used as the translating means. In this case, of course, the receiver is of the zero center type. When designed to measure such quantities as pressure or the position of a selsyn motor, the position of the gage or selsyn motor is converted into torque by means of spiral springs. For measuring temperature, the restraining and operating elements are combined into a single unit which is a standard differential type temperature instrument.

Conclusion

In combining standard instrument parts and electron tubes into a single unit which is self-compensating and which is capable of indicating and recording at a distance with instrument speed and accuracy, the usual type of measurements such as amperes, volts, watts, gas and liquid flow, temperature, pressure, and positions such as hydraulic head, water-wheel gate openings, and governor settings, a distinct forward step has been made in the field of telemetering.

The Application and Performance of Automatic Equipment

At Stations and Substations on the American Gas and Electric Company System

BY PHILIP SPORN,* Fellow, A.I.E.E. BASIL LANPHIER,* Member, A.I.E.E. and HAROLD E. TURNER* Associate, A.I.E.E.

INTRODUCTION

THE first urge behind the idea of automatic stations and substations was an economic one. Operators at many electric power stations were performing important functions, it is true, but the performance of these functions, frequently, was relatively simple and required but little of the operators' time. With the first real development of the relay art some fifteen years ago, it was realized that many operators' duties could be performed satisfactorily by relay arrangements. About the first and a most logical application of the automatic idea was to synchronous converters supplying railway load, followed closely by application to isolated hydro plants. The development of an economical and reliable universal motor mechanism made simple automatic switching stations possible; more complex automatic stations naturally followed with the development of synchronizing relays.

The developments just outlined were all based on the economic advantages derived. With the growth of automatic switching stations, however, it became apparent that they possessed another fundamental advantage. Under many circumstances they can act more quickly, more accurately, and more reliably than manual operators. Consequently, in some stations where for other reasons operators were required, automatic equipment took over many of the operators' functions.

This accounts for the parallel development of supervisory control equipment, automatic coal handling equipment, automatic combustion control, automatic frequency control, tie-line load control, etc. In all of these fields numerous applications have been made on the system with which the authors have been associated.

THE AUTOMATIC STATION AND ITS ELEMENTS

At almost any modern station certain features of station operation are automatic; thus a rotary will automatically pick up load called for by the trolley. Similarly many stations called "automatic" are really not entirely so. For example, standard reclosing circuits are generally made to lock out if the fault persists after a certain number of predetermined reclosures, after which manual attention is necessary.

An automatic station may then be defined as one which will place equipment on the line when a predetermined set of conditions (but they can be made as extensive and complicated or as simple as the designer chooses) has been reached, will continue to keep equipment on the line indefinitely or as long as there is a demand for it but will automatically remove any equipment that is at fault or feeding a fault, and, depending on a pre-arranged interpretation of various relay functions, will either lock it out at once or after a predetermined number of trials at reclosure. There are, of course, some exceptions to this definition.

It is evident that before automatic practise could be developed to its present state, much preliminary and basic work had to be done. This work was divided into two parts. First, a foundation of sound ideas was required and second, certain items of equipment were needed and had to be developed because they were either of a totally different nature than any required before, or because their application was different. These ideas and this equipment constitute the elements of the automatic station and from them all types and combinations of automatic stations in service today have been built up.

The development of the economic aspect in automatic station engineering was one of the most important of the ideas referred to above. The very early engineering layouts for automatic stations because of the limited amount of experience that was available with such equipment, were very naturally highly conservative. An attempt was made to cover and protect for all contingencies that had ever been experienced and a great many that could theoretically be experienced in the operation of a system. This naturally resulted in a multiplicity of protective devices that might have worked and justified themselves, if they were ever called upon to function, but which probably could not be justified economically in the vast majority of cases. The insistence on the part of some of the early sponsors of automatic stations on the necessity of protecting for all these contingencies with the resulting necessity for all these devices, not only produced a cost that worked against the automatic installation in many cases, but also resulted in an excessive amount of caution on the part of utility system engineers before approving automatic applications. When it was insisted upon that every piece of apparatus specified meet an economic as well as an engineering test (which was in reality, therefore, only a full engineering test), a great many devices were eliminated. This not only simplified the average automatic board, but also

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TABLE I—SUMMARY OF AUTOMATIC STATIONS AND EQUIPMENT ON PROPERTIES OF AMERICAN GAS AND ELECTRIC COMPANY

Installation No.	Type of service	Company	Date installed	Location	Station	Voltage Kv.	Transformer capacity Kva.	Equipment controlled
1	Distribution and sectionalizing station on urban high-voltage belt	Appalachian Elec. Power Co.	1931	Huntington, W. Va.	East 18th St.	33/4	5,000	3—44-kv. supply lines; 5—44-kv. feeders; 11—4-kv. feeders
2			1931	Huntington, W. Va.	Johnson Lane	33/4	7,500	2—33-kv. supply lines; 2—33-kv. feeders
3			1928	Roanoke, Va.	Mason Creek	11	630	2—11-kv. supply lines; 2—11-kv. feeders
4		Atlantic City Elec. Co.	1927	Atlantic City, N. J.	Inlet	22/4	6,000	2—22-kv. supply lines; 4—4-kv. feeders
5		Indiana & Michigan Elec. Co.	1927	So. Bend, Ind.	East Side	27/4	3,000	2—27-kv. supply lines; 4—4-kv. feeders
6			1928	So. Bend, Ind.	South Side	27/4	3,000	2—27-kv. supply lines; 3—27-kv. feeders; 4—4-kv. feeders
7			1930	So. Bend, Ind.	West Side	27/4	12,000	2—27-kv. supply lines; 5—4-kv. feeders
8		Indiana General Service Co.	1928	Muncie, Ind.	Blaine St.	33/4/2.3	6,750	2—33-kv. supply lines; 5—4-kv. feeders; 2—2.3-kv. feeders
9			1928	Muncie, Ind.	Sampson Ave.	33/4	12,000	2—33-kv. supply lines; 8—4-kv. feeders
10		Ohio Power Co.	1925	Canton, Ohio	Eighth St.	22/4	7,000	2—22-kv. supply lines; 1—22-kv. feeder; 5—4 kv. feeders
11			1927	Lima, Ohio	South Side	33/4	3,000	2—33-kv. supply lines
12			1927	Spencerville, O.	Spencerville	33/4	2,000	2—33-kv. feeders
13	Sectionalizing station on urban high-voltage belt	Ohio Power Co.	1925	Canton, Ohio	Bryan Ave.	22	..	4—22-kv. supply lines
14			1925	Canton, Ohio	Harrisburg Road	22	..	3—22-kv. supply lines; 2—22-kv. industrial feeders
15	Distribution and sectionalizing station on high-voltage transmission belt	Appalachian Elec. Power Co.	1929	Allen, Ky.	Allen	44/6.6	450	2—44-kv. supply lines; 1—44-kv. feeder; 1—6.6-kv. feeder
16			1930	Bartley, W. Va.	Bartley	13.2/2.3	2,700	2—13.2-kv. supply lines
17			1930	Caples, W. Va.	Caples	13.2/2.3	1,500	3—13.2-kv. supply lines
18			1928	Radford, Va.	Radford	33/4	1,500	2—33-kv. supply lines; 2—4-kv. feeders
19			1930	Bluefield, W. Va.	Winding Gulf	13.2/2.3	600	2—13.2-kv. supply lines
20			1930	Yukon, W. Va.	Yukon	13.2/2.3	1,500	2—13.2-kv. supply lines
21		Atlantic City Elec. Co	1928	Mullica Hill, N. J.	Mullica Hill	33/4	150	1—33-kv. supply line; 1—33-kv. feeder
22		Ind. & Mich. Elec. Co.	1928	Mishawaka, Ind.	Mishawaka City	27/4	3,000	1—27-kv. supply line
23		Ohio Power Co.	1930	East Sparta, O.	East Sparta	22/6.6	1,800	2—22-kv. supply lines; 3—6.6-kv. feeders
24			1928	Martins Ferry, O.	Martins Ferry	66/2.3	2,000	2—66-kv. supply lines
25			1930	Van Wert, Ohio	Van Wert	33/4	4,500	1—4-kv. feeder to condenser
26			1927	Yorkville, Ohio	Yorkville	66/4	1,750	2—66-kv. supply lines; 1—4-kv. feeder
27	Sectionalizing station on high-voltage transmission belt	Appalachian Elec. Power Co.	1930	Elkhorn City, Ky.	Elkhorn City	44/88	5,000	Ties 44-kv. and 88-kv. systems together
28			1929	Elwood, Ky.	Elwood	44	..	3—44-kv. supply lines
29			1930	Pekin, Ohio	Pekin	22	..	2—22-kv. supply lines; 1—22-kv. feeder
30	Urban distribution station served by at least two high-voltage feeders	Appalachian Elec. Power Co.	1928	Ashland, Ky.	Ashland	33/4	8,100	2—33-kv. supply lines; 9—4-kv. feeders
31			1930	Charlestown, W. Va.	Brooks St.	44/4	7,500	2—44-kv. supply lines; 7—4-kv. feeders
32			1928	Roanoke, Va.	Campbell Ave.	33/11/4	6,000	2—33-kv. supply lines; 1—33-kv. feeder; 8-4-kv. feeders; 1-11-kv. feeder
33			1930	Charlestown, W. Va.	Central Ave.	44/4	2,250	2—44-kv. supply lines; 4—4-kv. feeders
34			1928	Huntington, W. Va.	Four Pole Creek	33/4	1,500	2—33-kv. supply lines; 4—4-kv. feeders
35		Atlantic City Elec. Co.	1931	Beach Haven, N. J.	Beach Haven	22/4	2,000	2—22-kv. supply lines; 3—4-kv. feeders
36			1927	Atlantic City, N. J.	Chelsea	22/4	6,000	2—22-kv. supply lines; 4—4-kv. feeders
37			1924	Ventnor, N. J.	Ventnor	22/4	3,000	2—22-kv. supply lines; 4—4-kv. feeders
38			1929	Williamstown, N. J.	Williamstown	66/33/4	11,500	2—66-kv. supply lines; 3—33-kv. supply lines; 1—4-kv. feeder
39		Ind. & Mich. Elec. Co.	1926	Benton Harbor, Mich.	Benton Harbor	27/4/0.6	6,750	3—600 volt feeders
40		Indiana General Service Co.	1930	Marion, Ind.	Marion Steam Pl't.	33/4	15,000	3—33-kv. feeders; 9—4-kv. feeders
41			1928	Marion, Ind.	South Side	33/4	2,000	2—33-kv. supply lines; 3—4-kv. feeders
42		Ohio Power Co.	1929	Ironton, Ohio	Center St.	33/4	3,000	2—33-kv. supply lines; 4—4-kv. feeders
43			1930	Zanesville, Ohio	Cooper Mill	22/4	3,000	3—22-kv. supply lines; 4—4-kv. feeders
44			1930	Zanesville, Ohio	Linden Ave.	22/4	3,000	2—22-kv. supply lines; 3—4-kv. feeders
45			1930	Canton, Ohio	Meyers Lake	22/4	1,500	1—22-kv. feeder
46			1930	Zanesville, Ohio	North St.	22/2.3	6,000	2—22-kv. supply lines; 6—2.3-kv. feeders
47			1929	Ironton, Ohio	Pleasant St.	33/4	3,000	2—22-kv. supply lines; 2—22-kv. feeders
48			1929	Steubenville, Ohio	Stanton	22/4	3,000	2—22-kv. supply lines; 3—4-kv. feeders
49			1931	Scranton, Pa.	South Side	22/4	9,000	2—22-kv. supply lines; 4—4-kv. feeders; 1—4-kv. emergency feeder
50			1930	Moundsville, W. Va.	Moundsville	66/4	4,000	2—66-kv. supply lines; 1—66-kv. feeder; 5—4-kv. feeders
51	High-voltage sectionalizing and industrial distribution station	Appalachian Elec. Power Co.	1930	Belle, W. Va.	Belle	44	..	4—44-kv. supply lines; 4—44-kv. industrial feeders
52			1928	Charlestown, W. Va.	Chemical	44	..	4—44-kv. supply lines; 2—44-kv. industrial feeders
53			1927	Leewood, W. Va.	Leewood	44	..	3—44-kv. supply lines; 1—44-kv. feeder
54			1928	Russell, Ky.	Raceland	33/2.3	6,750	2—33-kv. supply lines; 1—33-kv. feeder; 2—2.3-kv. feeders
55			1927	Russell, Ky.	Russell	33/2.3	3,000	2—33-kv. supply lines; 1—33-kv. feeder; 5—2.3-kv. feeders
56			1927	Smithers Creek, Va.	Smithers Creek	44/2.3	1,000	2—44-kv. supply lines
57			1930	Van Lear, Ky.	Van Lear	44/40	4,500	Ties 44-kv. and 40-kv. systems together
58		Atlantic City Elec. Co.	1931	Bridgeton, N. J.	Laurel St.	66/13.2	12,500	2—66-kv. supply lines
29			1931	Paulsboro, N. J.	Paulsboro	33/4	9,000	2—33-kv. supplt lines; 2—33-kv. feeders; 4—4-kv. feeders
60		Indiana & Michigan Elec. Co.	1930	St. Joseph, Mich.	Auto Specialties	27/4	6,000	2—27-kv. supply lines
61			1928	Niles, Mich.	Niles	27	..	4—27-kv. supply lines; 1—27-kv. feeder
62			1928	Elkhart, Ind.	Northwest	27/4	3,000	2—27-kv. supply lines; 4—4-kv. feeders
63			1929	Mishawaka, Ind.	Rubber Regen.	27/0.46	2,000	1—27 supply line
64		Indiana General Service Co.	1928	Anderson, Ind.	Delco-Remy	33/4	4,500	2—33-kv. supply lines
65			1930	Muncie, Ind.	Elmridge	33/4	4,500	2—33-kv. supply lines; 2—4-kv. feeders
66			1926	Gas City, Ind.	Gas City	33/2.3	2,000	2—33-kv. supply lines; 4—2.3-kv. feeders
67			1929	Anderson, Ind.	Madison	33/13.2	15,000	2—33-kv. supply lines; 2—33-kv. feeders; 2—13.2-kv. feeders
68		Scranton Elec. Co.	1927	Avoca, Pa.	Avoca	22/4	3,000	3—22-kv. supply lines; 4—4-kv. feeders
69			1927	Old Forge, Pa.	Old Forge	66/22/4	15,000	3—22-kv. feeders
70		Wheeling Elec. Co.	1927	Benwood, W. Va.	Benwood	66/4	4,500	2—66-kv. supply lines; 5—4-kv. feeders
71			1929	Wheeling, W. Va.	Elm Grove	4	2,000	4—4-kv. supply lines; 2—625 v. d.c. feeders
72		The Ohio Power Co.	1929	Steubenville, Ohio	Fort Steuben	66	25,000	4—66-kv. supply lines; 2—66-kv. feeders

TABLE I—SUMMARY OF AUTOMATIC STATIONS AND EQUIPMENT ON PROPERTIES OF AMERICAN GAS AND ELECTRIC COMPANY—*Continued*

Installation No.	Type of service	Company	Date installed	Location	Station	Voltage Kv.	Transformer capacity Kva.	Equipment controlled
73	High-voltage sectionalizing station	Appalachian Elec. Power Co.	1927	Ashland, Ky.	Bellefonte	33/6.9	10,000	1—6.9-kv. feeder. High-voltage switching under "Supervising Control"
74			1928	Bowyer Falls, W. Va.	Bowyer	44/13.2	4,500	Ties 44-kv. and 13.2-kv. system together
75			1927	Near Cranberry, W. Va.	Prosperity	44	..	2—44-kv. supply lines
76			1927	Sophia, W. Va	Sophia	44	..	4—44-kv. supply lines
77		The Ohio Power Co.	1927	Rutland, Ohio	Rutland	132/33	4,500	2—33-kv. supply lines; 1—33-kv. feeder
78	Low-voltage distribution station	Appalachian Elec. Power Co.	1930	Burton, Ky	Burton	44/6.6	750	3—6.6-kv. feeders
79			1928	Williamson, W. Va.	Williamson	44/2.3	4,000	10—2.3-kv. feeders
80			1931	Garrett, Ky	Garrett	44/6.6	750	3—6.6-kv. feeders
81		Atlantic City Elec. Co.	1927	Linwood, N. J.	Belle Haven	22/4	1,750	2—4-kv. feeders
82			1927	Berlin, N. J.	Berlin	22/4	5,500	3—4-kv. feeders
83			1927	Pennsgrove, N. J.	Pennsgrove	33/2.3	600	2—2.3-kv. feeders
84			1930	Sea Isle City, N. J.	Sea Isle	22/4	500	2—4-kv. supply lines
85			1929	Stone Harbor, N. J.	Stone Harbor	22/4	600	2—4-kv. feeders
86		Indiana & Michigan Elec. Co.	1931	Lakeside, Mich.	Lakeside	27/6.9	1,000	2—6.9-kv. feeders
87			1931	New Buffalo, Mich.	New Buffalo	27/2.3	450	2—2.3-kv. feeders
88		Wheeling Elec. Co.	1929	Wheeling, W. Va.	County Line	66/4	7,500	6—4-kv. feeders
89			1930	Wheeling, W. Va.	Fulton	66/4	3,000	4—4-kv. feeders
90	Rotary converter station	Appalachian Elec. Power Co.	1924	Near Welch, W. Va.	Boissevain	13.2/0.41/0.2	505	1—500-kv. rotary converter
91			1924	Near Welch, W. Va.	Cherokee	13.2/0.41	300	1—300-kw. rotary converter
92			1921	Eckman, W. Va.	Eckman	13.2/.206	900	2—300-kw. rotary converters
93			1925	Near Faraday, W. Va.	Faraday No. 1	13.2/.206	600	2—300-kw. rotary converters
94			1929	Near Faraday, W. Va.	Faraday No. 30	13.2/.206	300	1—300-kw. rotary converter
95			1923	Near Welch, W. Va.	Itman No. 1	13.2/.206/.105	510	1—300-kw. rotary converter; 1—200-kw. rotary converter
96			1931	Near Newhall, W. Va.	Jacobs Fork No. 1	13.2/.206	550	1—500-kw. rotary converter
97			1931	Near Newhall, W. Va.	Jacobs Fork No. 2	13.2/.206	550	1—500-kv. rotary converter
98			1926	Jenkins Jones, W. Va.	Jenkins Jones	13.2/0.41	1,230	1—500-kw. rotary converter; 1—600-volt d.c. feeder
3			1928	Roanoke, Va.	Mason Creek	11/.41	630	2—300-kw. rotary converter
1	Rectifier station		1931	Huntington, W. Va.	East 18th St.	33/4	5,000	1—500-kw. rectifier; 2—600-volt d.c. feeders
99			1927	Rolfe, Va.	Rolfe	13.2/2.3	900	1—300-kw. rectifier; 1—600-volt d.c. feeder
2			1931	Huntington, W. Va.	Johnson Lane	33/4	7,500	1—500-kw. rectifier
69		Wheeling Elec. Co.	1929	Wheeling, W. Va.	Elm Grove	4/.625	2,000	2—1,000-kw. rectifier; 8—600-volt d.c. feeders
70	Supervisory control	Appalachian Elec. Power Co.	1928	Ashland, Ky.	Bellefonte	33/6.9	10,000	2—33-kv. supply lines; 8—33-kv. feeders
100			1930	Ivanhoe, Va.	Ivanhoe	88/13.2	30,000	3—88-kv. supply lines; 2—13.2-kv. supply lines; 5—13.2-kv. feeders
101			1927	Kingsport, Ky.	Cherokee	22/4	9,500	2—22-kv. supply lines; 3—4-kv. feeders
102		Ohio Power Co.	1925	Lima, Ohio	Rockhill	33/4/2.3	7,500	2—132-kv. supply lines; 2—33-kv. feeders
103	Coal handling	Appalachian Elec. Power Co.	1927	Glenlyn, Va.	Glenlyn	132/88/13.2	135,300	1 crusher; 1 coal screen; 3 belt conveyers; 2 pan conveyers
104			1926	Logan, W. Va.	Logan	132/44/2.3	72,000	1 crusher; 8 conveyers
105		Atlantic City Elec. Co.	1930	Deepwater, N. J.	Deepwater	66/33/11	199,000	1 crusher; 10 conveyers
106		Ind. & Mich. Elec. Co.	1925	Mishawaka, Ind.	Twin Branch	132/11/2.3	96,000	6 crushers; 8 conveyers
107		Ohio Power Co.	1924	Philo, Ohio	Philo	132/11/2.3	241,000	4 crushers; 8 conveyers; 2 coal screens
108			1917	Beech Bottom, W. Va.	Windsor	132/66/11	190,000	12 conveyers
109		Scranton Elec. Co.	1927	Pittston, Pa.	Stanton	66/11	107,500	2 crushers; 4 conveyers; 2 coal screens
110	Combustion control	Appalachian Elec. Power Co.	1929	Cabin Creek, W. Va.	Cabin Creek	132/44/6.9	136,500	1 boiler, stoker fired; 2 boilers, pulverized fuel (Leeds & Northrup)
103			1931	Glenlyn, Va.	Glenlyn	132/88/13.2	135,300	1 boiler, pulverized fuel (Bailey)
111			1928	Kenova, W. Va.	Kenova	33/11	71,000	5 boiler, stoker fired (Smoot)
105		Atlantic City Elec. Co.	1930	Deepwater, N. J.	Deepwater	66/33/11	199,000	6 boilers, pulverized fuel (Smoot)
112			1929	Atlantic City, N. J.	Missouri Ave.	66/22/11	107,500	2 boilers, stoker fired (Leeds & Northrup)
107		Ohio Power Co.	1931	Philo, Ohio	Philo	132/11/2.3	241,000	2 boilers, pulverized fuel (Leeds & Northrup)
73	Synchronous condenser	Appalachian Elec. Power Co.	1928	Ashland, Ky.	Bellefonte	33/6.9	10,000	1—7,500-kva. synchronous condenser
1			1931	Huntington, W. Va.	East 18th St.	33/4	5,000	1—5,000-kva. semi-automatic synchronous condenser
39		Indiana & Michigan Elec. Co.	1926	Benton Harbor, Mich.	Benton Harbor	27/4	6,750	1— 5,000-kva. semi-automatic synchronous condenser
113			1930	Benton Harbor, Mich.	Riverside	132/27/11	30,000	1—15,000-kva. synchronous condenser
7			1930	South Bend, Ind.	West Side	27/4	12,000	1— 7,500-kva. synchronous condenser
114		Ohio Power Co.	1930	New Boston, Ohio	Millbrook Park	33/2.3	8,500	1—7,500-kva. synchronous condenser
46			1930	Zanesville, Ohio	North St.	22/2.3	6,000	1—7,500-kva. synchronous condenser
25			1930	Van Wert, Ohio	Van Wert	33/4	4,500	1—2,500-kva. semi-automatic synchronous condenser
115	Generating station	Appal. Elec. Pr. Co.	1928	Rocky Mt., Va.	Rocky Mt.	2.3	..	1—187-kva. water wheel generator (vertical)
107	Frequency control	The Ohio Power Co.	1931	Philo, Ohio	Philo	132/11/2.3	241,000	G. E. (Warren)*; (Leeds and Northrup)*
108			1929	Beech Bottom, W. Va.	Windsor	132/66/11	190,000	G. E. (Warren)*; (Leeds and Northrup)*

Note: Since the preparation of this paper 6 additional automatic substations have been installed.

*Experimental equipment.

greatly reduced its cost. From both standpoints the natural result was the opening up of the field of application of automatic stations.

Some of the principal problems which had to be worked out in the development of the equipment elements, are given in the following paragraphs.

Relays—General. It was necessary, in general, to redesign relays before they could meet the requirements of automatic work. For this application, where their unsupervised performance had to be depended upon for proper operation of a station, they had to be absolutely reliable and accurate in operation and require very little maintenance. In addition, many new relays had to be developed to perform functions which hitherto had been taken care of manually.

Motor Mechanisms. To make the simple automatic switching station possible, sturdy, compact, and reliable devices for operating oil circuit breaker mechanisms had to be developed with the essential requirement of operation from an a-c. source.

Reclosing Relays. It was necessary to develop a-c. energized timing relays for use in combination with breaker motor mechanisms to make definite reclosing cycles possible. These relays had to provide not only for reclosures at adjustable time intervals, but also lock out features after a definite number of unsuccessful reclosures.

Synchronizing and Check Synchronizing Relays. To make complex automatic switching possible devices were developed which would perform the functions of synchronizing automatically; which would check conditions of voltage magnitude and phase relation and difference in frequency of two systems, and when conditions were all proper, supply the starting impulse to close a selected breaker to synchronize these systems. Check synchronizing devices were also needed for supervising the closing of two parts of the same system under conditions when these parts were already tied together through another circuit.

Energizing Transformers. One of the most important elements of an automatic switching station is the energizing transformer. The reliability of the station depends on the reliability of this element. Transformers with improved design and construction of windings and bushings and proper coordination between these had to be developed from the distribution and potential types to furnish from a line or bus the necessary power for energizing the automatic equipment.

The reliability of these present day automatic station elements has been made possible only by much labor and as the result of much experience. The history of this development is by itself very interesting, but cannot be covered in this paper.

However, the manner in which these various fundamental elements and ideas are combined in the development of automatic stations and systems on the properties of the various subsidiaries of the American Gas and Electric Company is described below.

Development of Automatic Equipment on the American Gas and Electric Company System

The development of automatic equipment on the system of the American Gas and Electric Company consisted of two distinct phases. The first phase consisted principally of the development and installation of automatic synchronous converter substations for mine service and an installation for serving traction load, all confined to two divisions of the Appalachian Electric Power Company. The second phase has consisted of a very extensive and general development over the whole American Gas and Electric Company system of automatic substation switching equipment, automatic control for station and substation equipment, the development of supervisory control, the development of automatic frequency and tie-line control, and, in the steam end of generating stations, the development of automatic coal handling and combustion control. The extensiveness of the application is shown in Table I. It will be seen that a total of 115 automatic stations or applications has been made covering practically the entire field of automatic work.

A classification of all automatic stations or equipment according to type of service is given in Table I.

The development and the use of the listed automatic equipment on the American Gas and Electric Company system, with the exception only of the first synchronous converter equipments, have been under the supervision of the authors. There will be described below the successive steps in this development, from the engineering and operating standpoints, with particular reference to automatic switching for transmission and distribution substations. Automatic synchronous converter installations have been standardized and well understood for some time and are indicated only to show the extent to which they have been used. Coal handling, combustion control and frequency control, too, have been included in Table I to show the extent to which applications of such equipment have been made and to point them out as fields in which automatic control is rapidly being extended.

Development on the System of The Ohio Power Company

Canton 22-Kv. System. The first extensive use of automatic switching equipment by the American Gas and Electric Company was on the 22-kv. system of The Ohio Power Company serving the city of Canton and environs. The load in this area is approximately 80,000 kw. It is divided into two principal classes, in the first of which are included several very large industrial loads, totaling approximately 50,000 kw., served directly at 22 kv.; in the second are included residential, commercial, and small industrial loads, totaling approximately 30,000 kw. All this load is served from the Sunnyside Substation, which is both an important 132-kv. switching station and a 132/22-kv. step-down station of approximately 90,000 kva. capacity.

Originally load in this area was served from the Sunnyside Substation at 22,000 volts by means of radial feeders terminating through disconnect switches in step-down distribution substations which could, however, be connected with one another by means of emergency circuits switched through disconnect switches. With this arrangement, it was necessary, particularly in times of trouble or during severe storms, to place operators at the various substations to operate the disconnect switches as one or another circuit became affected by trouble, so as to maintain service to all the distribution points.

After thorough study it was decided to install automatically operated oil switches at all these stations and by a proper grouping of the various feeders and interconnecting emergency circuits to provide a loop system. The installation of these automatic substations not only solved the service problems, but, by permitting complete parallelism of high-voltage feeders greatly improved the voltage situation. It permitted, of course, the elimination of emergency operators.

A map of the city of Canton and environs on which has been spotted the location of the various substations is shown in Fig. 1. Fig. 2 is a one-line diagram showing

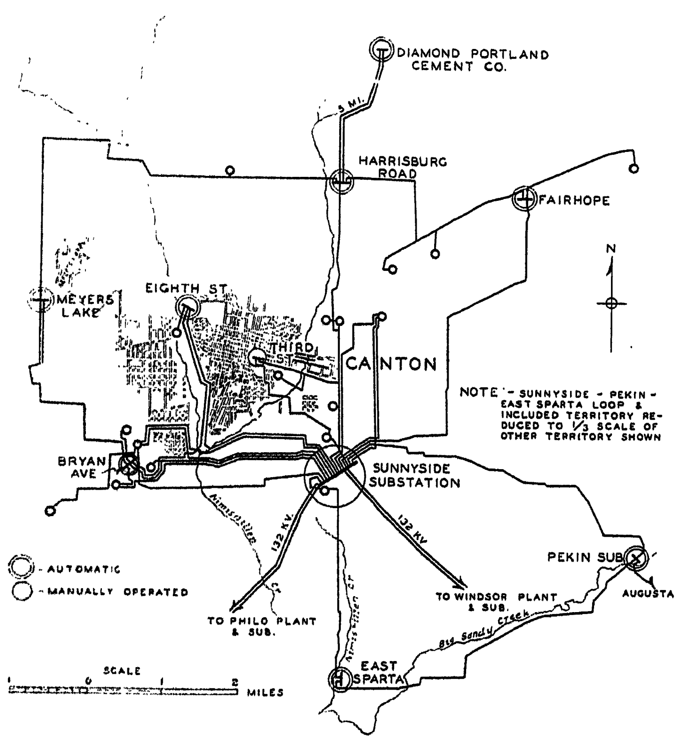

FIG. 1—MAP SHOWING LOCATIONS OF THE AUTOMATIC SUBSTATIONS ON THE 22-KV. TRANSMISSION LOOP SURROUNDING THE CITY OF CANTON, OHIO

the loop circuits connecting the automatic substations and the location of oil switches. The attended stations are (1) Sunnyside Substation and (2) Third Street Substation. The former is the principal dispatching point for a large number of 132-kv. circuits terminating there. The latter is a part of a station used to supply steam heat for a considerable area from turbine or engine exhaust. Except for these two stations, the entire area is served by the group of eight automatic stations indicated. Each of these, as will again be seen from Fig. 2, has at least two sources of supply.

The automatic equipment and relaying used at Bryan Avenue is typical of the substations on this particular

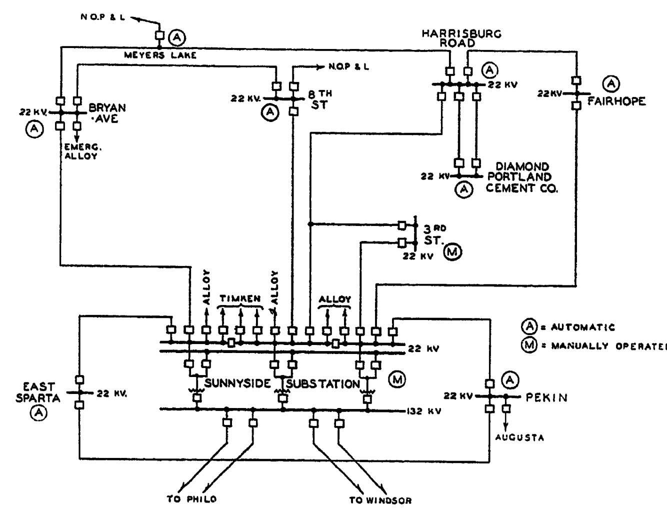

FIG. 2—DIAGRAM OF THE CANTON 22-KV. SYSTEM SHOWING THE SWITCHING ARRANGEMENT AT THE VARIOUS SUBSTATIONS

system. This early installation of reclosing equipment represented a departure from the then recommended practise since none of the ordinary undervoltage and overvoltage relays were employed. Because of the arrangement of the loop circuits shown in Fig. 2, it was not necessary to provide automatic synchronizing and consequently, it was possible to use very simple reclosing circuits and devices. A direct line from Sunnyside is the principal feed and the Sunnyside switch at Bryan Avenue is controlled so that it will reclose after tripping, provided the line from the Sunnyside Substation is energized at normal voltage and with the proper phase sequence; this, consequently, puts the operation of this switch at Bryan Avenue under limited control of the Sunnyside operator. The Harrisburg Road and the Eighth Street lines at this station tie, back through other automatic stations to the Sunnyside Substation. The switches on these two feeders are controlled by a motor-driven lockout timing relay, which will reclose each feeder twice and then lock out upon the occurrence of trouble which persists for longer than the time for which the reclosing relay provides. A fourth circuit is located at Bryan Avenue, operating as a stub feeder, with equipment similar to that on the Harrisburg Road and Eighth Street feeders, to act as an emergency feed to the Alloy Substation. It can also, by suitable switching, be used as an additional source of power from Sunnyside to the Bryan Avenue Substation.

All breakers at Bryan Avenue are protected by induction overload and reverse power relays, which will trip

a breaker for power flow (of sufficient magnitude) away from the bus. Bus trouble here will trip the switches at Sunnyside, Eighth Street, and Harrisburg Road. The switches at Bryan Avenue and Harrisburg Road, if the trouble persists, will, after two reclosures, lock out; the Sunnyside operator, after trying his line once or twice, will leave his Bryan Avenue switch open until the trouble has been cleared up.

The present (1932) practise is to provide, at such substations, bus differential protective relays which, for a case of bus trouble will trip out all switches at a substation and lock them out until the trouble has been cleared up and the lock out relays reset by hand. Such protection, which is relatively inexpensive, prevents the loss of tap-off loads on the lines serving the substation in trouble. Furthermore, the faulty bus is quickly cleared and damage held to a minimum.

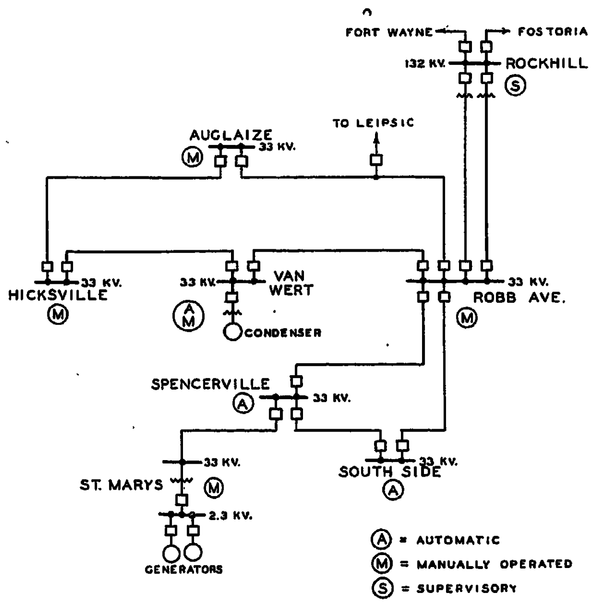

FIG. 3—SWITCHING DIAGRAM OF THE LIMA AND NORTHWESTERN DIVISIONS OF THE OHIO POWER COMPANY

In later installations the scheme employed for such lines as the one from Sunnyside, serving Bryan Avenue, has been somewhat modified. The reclosing relay now employed at Bryan Avenue on this line will reclose the Sunnyside breaker as soon as the line is energized and the voltages have the correct phase rotation, but in more recent practise a relay with a lockout feature is used and set to allow the switch to reclose twice only, after which it will lock out. This was done, since with the older type of relay, if the breaker mechanism should fail to latch properly, the breaker would continue to be reclosed so long as the line was energized.

In the original Canton automatic equipments, as has been pointed out, phase checking relays were provided. Experience has shown, however, that on loops of this type there is such a small likelihood of phase reversal that the expense of protection is hardly warranted. These relays are not being used therefore, in present practise, in situations of that sort.

The Lima 33-Kv. System. Fig. 3 shows the 33-kv. transmission system in the Lima District. A number of cities and large towns in an area of approximately 2,000 square miles is served from this system. The service is for the most part made up of residential, commercial, and small industrial loads.

The 33-kv. system is served from the 132-kv. step-down substation at Rockhill, Lima. The Rockhill Substation, the main point of supply, is controlled through supervisory equipment by the operators at the Robb Avenue Substation, the principal control and dispatching point for this system.

Automatic substations are located at Spencerville and South Side on one 33-kv. loop. The substations at Van Wert, Hicksville, and Auglaize on the other 33-kv. loop are manually controlled, because of present operating conditions, but they are so designed that they can easily be converted to automatic stations when the need for it arises. In view of this possibility, the synchronous condenser which was recently installed at Van Wert was made completely automatic with the exception of the initial starting impulse. This is at present provided from a control switch, but it is so arranged that when the station is made automatic, the control switch can be replaced by relays.

The substations at Spencerville and South Side have been automatized for approximately four years, and the considerations which led to the introduction of automatic equipment on this system were very similar to those which dictated the automatizing of the Canton 22-kv. system.

Because of the close supervision which the operator at Robb Avenue has over this loop, it was not necessary to provide automatic check synchronizing or synchronizing facilities. The Robb Avenue switch at the South Side Substation is provided with induction overcurrent and reverse power relays and trips for power flow (of sufficient magnitude) away from the bus. It will reclose whenever voltage of the proper phase sequence is established from Robb Avenue. The Spencerville breaker at South Side is provided with the same relay protection and will reclose twice if the Robb Avenue line is energized, after which it will lock out if the trouble still persists. Since both breakers are provided with reverse power relays, after one has tripped on trouble, the other cannot trip as there is no source of generating supply at the station. This makes it possible for the operator at Robb Avenue to tell from his indicating instruments what the setup of the loop is. At Spencerville the Robb Avenue and South Side switches are protected in the same way as the Robb Avenue and Spencerville switches at South Side, with the exception that provision is made at Spencerville by suitable interlocks so that the St. Mary's generating plant cannot be closed in out of parallel with the Lima system.

It will be noted that here again it was possible to set up the entire system on an automatic basis without resorting to synchronizing relays.

Automatic Development on the 66-Kv. System of the Wheeling Electric Company and the 66-Kv. System of the Sunnyside Division of The Ohio Power Company

The territory of the Wheeling Electric Company served by a 66-kv. transmission system which is contiguous to the 66-kv. system of The Ohio Power Company, presents an interesting example of automatic station practise.

The installation of automatically operated substations has facilitated the development of the Wheeling Electric Company system and the 66-kv. portion of The Ohio Power Company system along the Ohio River south of the Windsor Plant. Fig. 4 is a map showing geographically the extent of this system. Fig. 5 is a one-line diagram showing the arrangement of the substations and the switching.

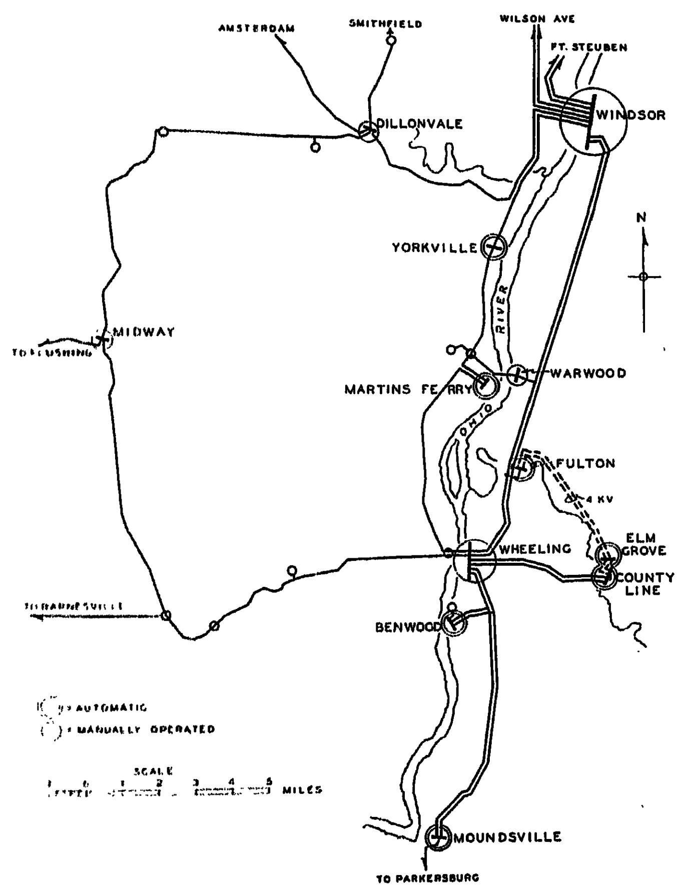

Fig. 4—Map Showing the Extent of the Territory Served by the 66-Kv. Transmission System South of Windsor to Moundsville and the Location of the Automatic Substations

The first automatic substation to be installed in this division was at Benwood, followed closely by installations at Martins Ferry and Yorkville. A short time later County Line and Elm Grove, and finally the Moundsville Substation, were installed.

When the Benwood Substation was first installed, it was fed by one 66-kv. circuit directly from the 42nd Street Substation at Wheeling, and by a tap to another 66-kv. circuit extending from the 42nd Street Substation and interconnecting with the system of the Monongahela-West Penn Power Company at Parkersburg. It was accordingly essential that some means for synchronizing the switches at Benwood be employed; hence,

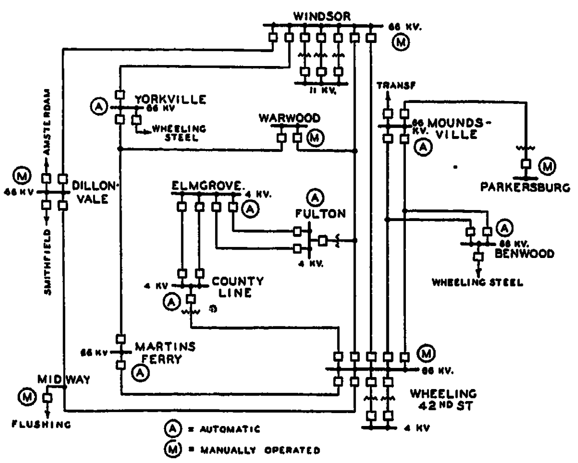

Fig. 5—One-Line Diagram of the Transmission System South of Windsor Supplying Wheeling, West Virginia, and the Surrounding Territory

the automatic equipment at this substation embodied the first installation of automatic synchronizing relays on the American Gas and Electric Company system. Each breaker at Benwood was provided with induction overload and reverse power relays arranged to trip for power flow (of sufficient magnitude) away from the Benwood bus. The automatic equipment was designed to reclose the breakers at Benwood (after the occurrence of trouble) upon reestablishment of voltage provided the Benwood bus itself was deenergized, or to reclose the breakers only through the synchronizing relays if the bus were energized.

Later, when the Moundsville Substation, located south of Benwood and serving the city of Moundsville was installed, the Benwood Substation was tapped to the two lines between the 42nd Street Substation and the Moundsville Substation. The principal automatic features of the Benwood Substation, however, remained the same. The operation of the Moundsville Substation is practically the same as that of the Benwood Substation.

The other automatic substations on this system do not use synchronizing or check synchronizing relays since they are not necessary except for the rare operating condition of losing all tie lines between Windsor and Wheeling. Experience has shown that this condition is so seldom encountered that provisions for taking care of it are not justified. Automatic reclosing is provided on the 4-kv. feeder circuits at Elm Grove and County Line Substations.

Development on the System of the Appalachian Electric Power Company

44-Kv. System South and East of Cabin Creek. The Cabin Creek Plant of the Charleston Division of the Appalachian Electric Power Company is located 16 miles up the Kanawha River from the city of Charleston. An extensive 44-kv. transmission system extends south and east from the Cabin Creek Plant to serve the mining loads of the large New River coal field. At the time this system first came into the American Gas and Electric Company group, the principal lines and switching were as shown in Fig. 6.

The important trunk lines of the system were those extending successively from Cabin Creek to Smithers Creek to Red Star to Prosperity to Sophia, and the lines from Cabin Creek to Leewood. It will be seen from the diagram that with the oil switches and sectionalizing disconnect switches shown in Fig. 6, the system was composed of a series of extended single lines or loops. Double taps were extensively used on the double-circuit lines for connecting other circuits to either one line or

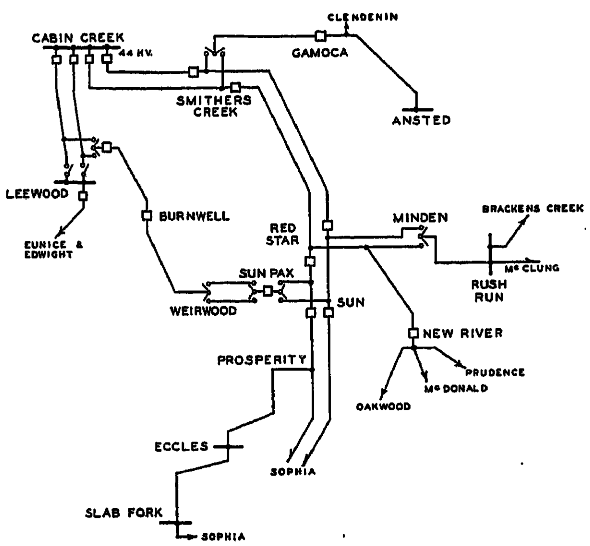

Fig. 6—44-Kv. Transmission System East of Cabin Creek as it was Before the Installation of Automatic Switching Stations

the other. It was practically impossible to obtain selective relaying with the switching scheme employed, and consequently the occurrence of trouble, particularly on the principal trunk lines, often involved loss of all sources of feed to large portions of the system. With some switching set-ups, as much as 200 miles of line were operated as a single circuit. Voltage conditions, particularly at remote points on the system, were poor and service was subjected to a great deal of interruption since trouble on one part of such a circuit was widespread in its effect.

The territory through which these lines run is very mountainous and inaccessible, and communication which was carried on entirely by wire telephone, was available only at certain points on the system and was entirely inadequate. All switching had to be done manually at scattered points and in times of trouble this presented a very serious problem.

It was apparent that this particular system was an ideal one for the application of automatic switching. The physical location of the transmission lines forming the backbone of the system made it possible, by the use of automatic substations strategically located, to group these lines and to provide reliable sources of feed with good automatic sectionalizing in times of trouble. Fig. 7 is a diagram of this system after the regrouping and

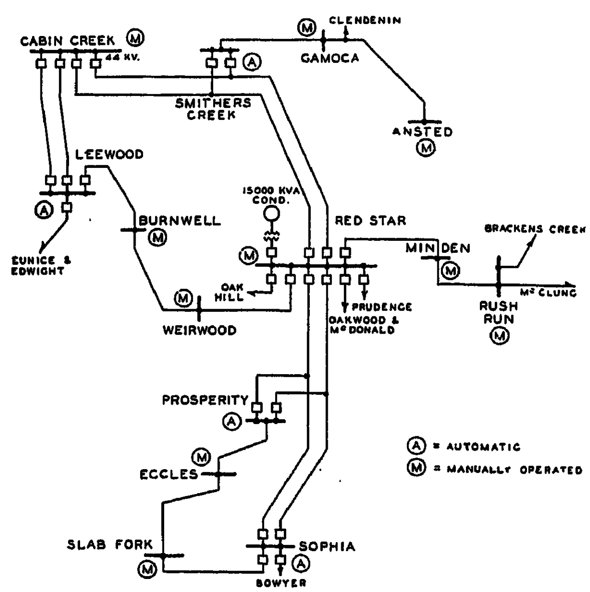

Fig. 7—Diagram of the 44-Kv. Transmission System East of Cabin Creek After the Installation of Automatic Switching Stations

sectionalizing of transmission lines was carried through.

The Red Star Substation was established at the load center of the system and the circuits so arranged and extended that it is fed by two lines from the 44-kv. bus at Cabin Creek and by one 44-kv. line from Leewood. A 15,000-kva. hydrogen cooled condenser was later installed at this station adequately to control system voltage. Full time operators are employed at this station, which is the only one on the system at which this practise is followed. Fully automatic substations were built at Smithers Creek, Prosperity, Sophia, and Leewood. An analysis of Fig. 7 will clearly show to what an extent the reliability and ease of operation of the system have been increased, and how small a portion of the system is affected by trouble on any one of the lines.

44-Kv. System West of Cabin Creek. Whereas the transmission system east of Cabin Creek is rather extensive and covers many hundreds of square miles of mountainous coal region, the system west of Cabin Creek is confined to the comparatively narrow valley of the Kanawha River. On both sides of the valley there are located large groups of chemical and other bulk

power consuming industries, industries which are particularly susceptible to interruptions in service and consequently require service of the highest type. Automatic stations have been applied with great success in the development of the transmission supply system to this valley.

The system of the Charleston Division of the Appalachian Electric Power Company, which extends between Cabin Creek and Turner Substation is shown in Fig. 8.

the preferred source of feed is over the two lines direct from Cabin Creek. The two tap-off lines are normally open at Belle, but in case of failure of voltage on the two lines from Cabin Creek, the Cabin Creek breakers at Belle trip and the tap-off breakers close to reenergize the substation bus. A view of the automatic board is shown in Fig. 10.

The Chemical Substation in Charleston also supplies a large chemical load area. It is fed by two lines direct

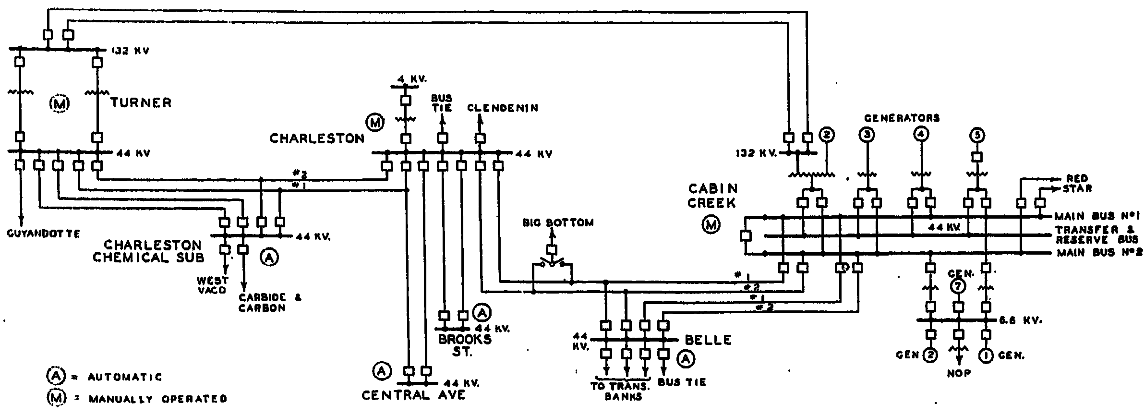

Fig. 8—One-Line System Diagram of the District West of Cabin Creek to Turner

The 44-kv. system extends along the Kanawha River, between these two points, which are in addition tied together by two 132-kv. lines. Several towns and cities, including as the principal one, the city of Charleston, West Virginia, and in addition the large industrial and chemical loads already mentioned, are served from this system. The automatic substations in this valley are Belle, Brooks Street, Central Avenue, and Chemical

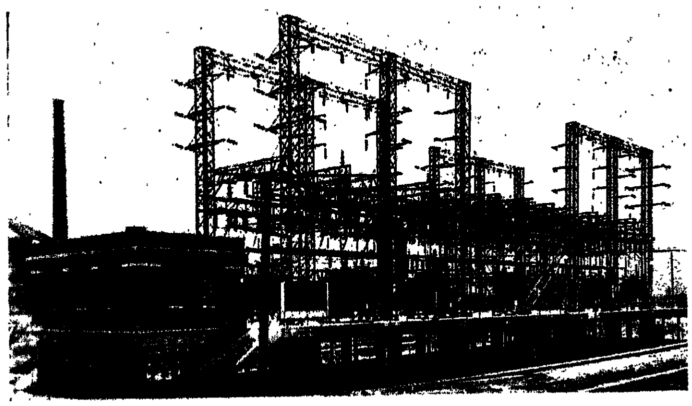

Fig. 9—The Belle Substation

Substations. The Belle Substation, one view of which is shown in Fig. 9, is one of the most important and feeds a large industrial chemical load. It has a present capacity of 45,000 kva. with provision for additional capacity later. Two 44-kv. incoming lines feed this station directly from Cabin Creek, and two other sources of feed are provided by tapping the two Charleston-Cabin Creek lines. To provide maximum security of service,

from the Turner-Charleston 44-kv. lines. The preferred scheme of reclosing is not employed at this substation, but provision is made so that any breaker will reclose from its line after the occurrence of trouble when the line has been reenergized.

The Brooks Street Substation, Fig. 11, and the

Fig. 10—Automatic Switchboard at Belle Substation

Central Avenue Substation, are step-down distribution substations serving the 4-kv. distribution system in the city of Charleston. The Brooks Street station is fed directly by two lines from the Capitol Hill Substation, and the Capitol Hill breakers at Brooks Street are

arranged to close automatically when the lines are energized from Capitol Hill. A 7,500-kva. transformer

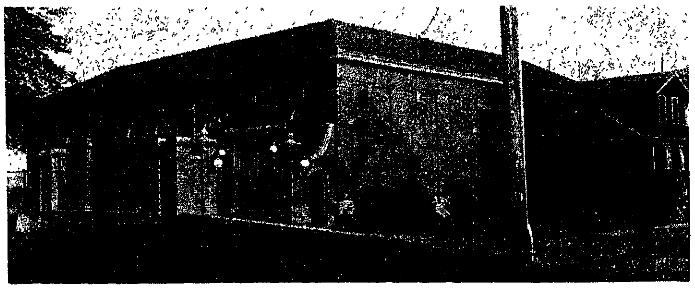

FIG. 11—BROOKS STREET SUBSTATION

A typical business and residential substation automatically operated

steps down to 4 kv. at which voltage 6 automatic reclosing distribution feeders are employed. The Central

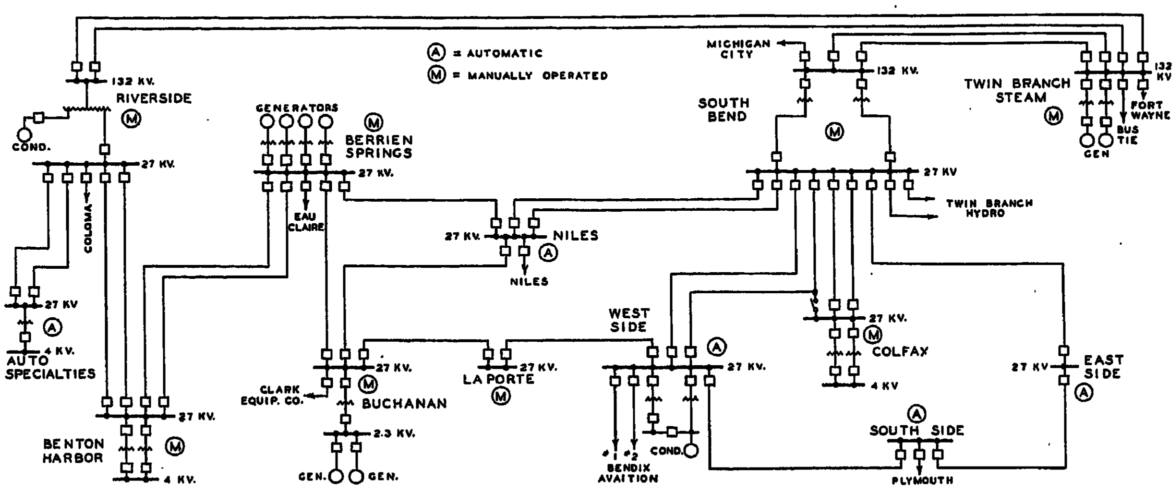

FIG. 12—ONE-LINE DIAGRAM OF THE INDIANA & MICHIGAN ELECTRIC COMPANY SYSTEM NORTH AND WEST FROM TWIN BRANCH PLANT SHOWING THE LOCATION OF THE AUTOMATIC STATIONS

Avenue Substation is fed by one line from Capitol Hill Substation and a tap connection from the Turner-Charleston No. 1 line. A preferred reclosing arrangement is used. For normal operation, the Capitol Hill breaker at Central Avenue is closed and the tap connection, which is used as an emergency supply, is automatically connected to the bus if the Capitol Hill feeder fails. When the Capitol Hill line is again energized, however, the Capitol Hill switch will reclose, and after a short period, will trip the emergency supply breaker.

DEVELOPMENT OF AUTOMATIC EQUIPMENT ON THE SYSTEM OF THE INDIANA & MICHIGAN ELECTRIC COMPANY

The Indiana & Michigan Electric Company presents a number of very interesting applications of automatic switching.

Fig. 12 is a diagram showing the 27-kv. loop of the Indiana & Michigan Electric Company serving the city of South Bend and the 27-kv. system serving the surrounding territory. The city of South Bend has a population of approximately 110,000 and the load in this area is approximately 40,000 kw., supplied principally from the 132-kv. switching and step-down substation with a capacity of 60,000 kva. The service consists of residential, commercial and small industrial loads in the city of South Bend, together with a number of large industrial plant loads.

The 27-kv. loop extending around the city of South Bend includes three automatic substations known as the South Side, East Side, and West Side Substations.

Originally the East Side and West Side Substations were the only substations in this group and no synchronizing or check synchronizing facilities were provided. Later, however, the substation at South Side was added and the West Side Substation was rebuilt and because of changes in the arrangement, whereby lines from other generating sources were tied into this loop, synchronizing features had to be provided at West Side and South Side.

At the East Side Substation, the feeder to the main step-down substation closes automatically with establishment of voltage on that line and the South Side switch closes when the 27-kv. bus is energized from the main step-down substation. A 3,000-kva. transformer bank steps down to 4 kv. and feeds four automatic reclosing 4-kv. distribution feeders. Fig. 13 is a front view of this substation, showing the type of building used in purely residential sections.

The South Side Substation on this loop is connected by a 27-kv. circuit to both the East Side and to the West Side Substations, and in addition is connected by a 27-kv. circuit to the system of the Northern Indiana Power Company at Plymouth, Indiana. Two 27-kv. stub reclosing circuits are also provided to feed a large industrial load. A 3,000-kva. transformer bank steps down to 4 kv. at which voltage four automatic 4-kv. feeders are employed. The East Side and West Side

breakers at South Side are provided with check synchronizing only. Full automatic synchronizing is provided for the Plymouth circuit.

The rebuilt West Side Substation is one of the most up-to-date of the fully automatic stations. Seven 27-kv. breakers at this station are automatically controlled. The 4,500-kva. step-down transformer feeds five automatic reclosing 4-kv. distribution circuits and a 7,500-kva. transformer supplies a synchronous condenser. The 27-kv. feeder switches going to the main step-down substation, the Laporte switch and the South Side switch are all equipped for full automatic synchronizing and check synchronizing. The two Bendix circuits are equipped to reclose automatically from the bus when it is energized. The condenser equipment is fully automatic. It starts up when the voltage varies more than a predetermined amount from normal (plus or minus one volt), and shuts down when the corrective kilovolt-ampere requirement reaches a definite minimum for a predetermined length of time. (200 kva. lag or lead for 3 minutes.)

The Niles Substation, Fig. 14, was installed at a time when no 132-kv. tie existed between the Northern and Southern parts of the Indiana & Michigan Electric Company system. This substation was an important tie point between the hydro plants at Buchanan and Berrien Springs and the South Bend 132-kv. substation. A large local industrial load is served by a 27-kv. feeder out of this substation. The switch on this circuit is provided with the usual automatic reclosing features. The other four circuits, *i. e.*, the two circuits to South Bend and the two circuits to Berrien Springs and Buchanan hydro plants, are provided with fully automatic

Fig. 13—East Side Substation, South Bend, Indiana

A typical automatically operated substation in a purely residential district

synchronizing and check synchronizing relays. In the two years that this substation operated before the 132-kv. tie was installed between the Benton Harbor and South Bend districts of the Indiana & Michigan Electric Company, it functioned perfectly.

There are several other automatic high-voltage installations on this system, such as the Mishawaka City Station (installation No. 22, Table I), the Rubber Regenerating Company station (installation No. 63, Table I), and the Northwest Station, Elkhart (installation No. 62, Table I), but none of these can be gone into beyond the extent covered in Table I.

Kentucky and West Virginia Power Company

The territory of the Kentucky and West Virginia Power Company is very different from that of many of the other companies of the American Gas and Electric Company group. This company serves principally coal

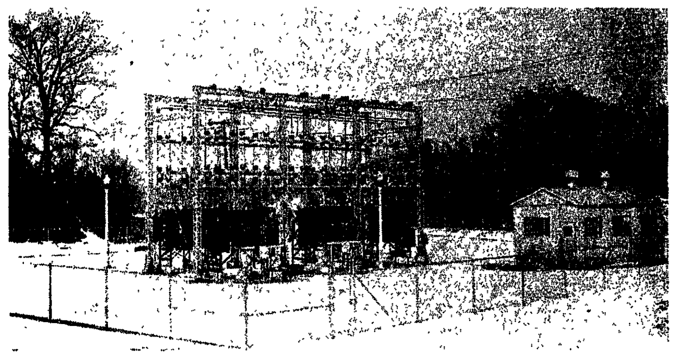

Fig. 14—Niles Automatic Switching Station

mine loads in the southeastern section of Kentucky. The topography of the country is unusually rough. A 44-kv. transmission network serves individual coal mines from substations tapped directly to the 44-kv. transmission line. It is necessary, in order to maintain the proper grade of service, to provide some form of loop service, but owing to the type of territory the transmission loops quite frequently have to be very long. From an operating standpoint, this has generally meant long and very expensive patrols upon the occurrence of a transmission line failure. The installation of a small number of sectionalizing stations automatically operated has not only greatly improved the service, but also made possible many operating economies.

In Fig. 15 is shown a diagram of the switching arrangement of that portion of the Kentucky and West Virginia Power Company supplied from the Beaver Creek Substation and from the Hazard Plant. The substations at Allen, Elwood, Elkhorn City, and Van Lear are all provided with automatic reclosing features. Approximate transmission distances are indicated to give a better idea of the type of system involved.

The Beaver Creek Substation is a 132/44-kv. switching and step-down station manually controlled. This station employed one of the first of the new type miniature switchboards.

The Allen Substation is connected directly to Beaver Creek by one 44-kv. line. Another line from Allen extends to the Elwood Station and back to Beaver Creek. Automatic reclosing and check synchronizing were provided on each of these switches.

The Substation at Van Lear feeds a coal company system on which generating capacity is normally operating. The substation at Elkhorn City ties in with the

system of the Appalachian Electric Power Company. Both of these substations, accordingly, are provided with check synchronizing and synchronizing relays.

A very interesting modification in the automatic equipment has recently been made to take care of certain operating conditions. The line between Elwood and Allen is a long one and if trouble occurs on this line and persists, the line is locked out at both ends, which would interrupt service to a considerable number of customers tapped to this line. It would particularly affect Pikeville, the county seat of the area. The problem could have been solved, of course, by the installation of an additional automatic sectionalizing point at Pikeville. It was felt, however, that such an expenditure was not warranted. Air break sectionalizing switches were therefore installed and the following modification in the automatic equipment at Elwood and Allen was made. Small telephone ringer circuit relays were installed on the line switches going to Pikeville at both Allen and Elwood. These relays can be energized from the wire telephone station at Pikeville to reclose the breakers on which they are installed and the breaker will

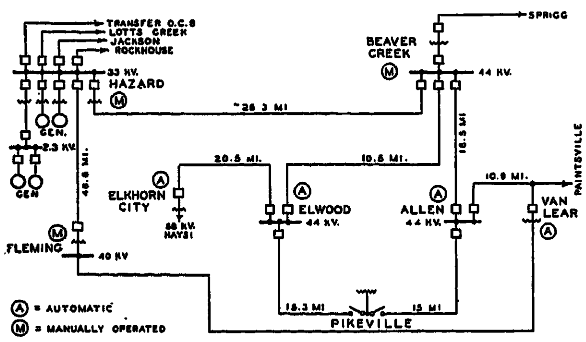

FIG. 15—ONE-LINE SWITCHING DIAGRAM OF THE KENTUCKY AND WEST VIRGINIA POWER COMPANY 44-KV. TRANSMISSION SYSTEM SHOWING AUTOMATIC INSTALLATIONS

stay in if the particular section is sound. The telephone relay is so wired that it will only act to reclose the breaker provided the breaker has previously gone through its reclosing cycle and locked out, and provided further that the substation bus at which the breaker is installed is energized.

LOW-VOLTAGE RECLOSING CIRCUITS

There are on the American Gas and Electric Company system approximately 50 substations at which low-voltage automatic reclosing equipment has been employed. There are approximately 260 breakers controlled in this manner and the voltage range of the circuits so controlled is from 2,300 to 6,900 volts. The breaker duty cycle usually employed is the 3 reclosure cycle. A first reclosure takes place after 15 seconds, a second reclosure 30 seconds later and a third reclosure 75 seconds later. This reclosing cycle is, of course, in some instances modified to meet individual requirements. The interrupting capacity of the breakers used in this class of service ranges approximately from 75,000 to 250,000 kva.

SUMMARY

The systems discussed, it is believed, have demonstrated the fact that there is practically nothing in the way of switching, whether switching of feeders, stations or systems involving one or many generating stations, that cannot be carried out and that has not been carried out completely and satisfactorily by automatic equipment.

SPECIAL AUTOMATIC INSTALLATIONS

In the foregoing description of automatic applications, stress has been laid on switching arrangements, the installations described covering practically every switching requirement. In addition to these, a considerable number of special equipments and applications has been made over the system, but because of lack of space, they cannot be described in detail in this paper. The following are some of those of particular interest:

Synchronous Condensers. While synchronous converters have been controlled automatically for over ten years, automatic control of synchronous condensers is comparatively recent. As shown in Table I, fully automatic or semi-automatic condensers are installed at eight places on the system. On these installations, protection is provided for failure of a-c. voltage, machine windings (differential), overload on starting compensator, overvoltage, continual overload of moderate amount, field failure, unbalanced phase currents, unbalanced or reverse phase incoming voltage, overheated bearings and rapid restarting.

Two of the completely automatic installations, *viz.*, those at West Side, South Bend, and North Street, Zanesville, come on the line automatically when the voltage is either too low or too high by a certain percentage for a definite length of time, and they are shut down when the need for corrective kilvoltampere of the machines is no longer present. This shutdown takes place when the condenser is supplying a minimum value of corrective kilvoltamperes at the proper voltage for a predetermined (but variable) length of time.

The essential difference between the full automatic and the semi-automatic installations is that the semi-automatic depends on a manually given starting impulse.

Mercury Arc Rectifiers. Although the development of the mercury arc rectifier is comparatively recent, a number of installations as shown in Table I has been very successfully automatized on the American Gas and Electric Company system. The installation at Elm Grove consists of two 1,000-kw. mercury arc rectifiers. The first unit is started from a clock switch, and the second when the load demand is beyond the capacity of the first. The two 500-kw. installations at Johnsons Lane and East 18th Street feed the railway load in the city of Huntington. The Johnsons Lane rectifier is

given the starting impulse by a manual control switch. The rectifier at East 18th Street starts automatically on low trolley voltage.

A 300-kw. fully automatic rectifier is installed at the Rolfe Substation and serves a mining load. It is supplied at 13.2 kv. and converts to 600 volts direct current. The station is operated without any attendance except the periodic inspections.

Automatic Synchronizer. The relay development that preceded and accompanied automatic station practise has resulted in the transfer of a considerable number of operators' functions to automatic equipment at attended stations and substations. One of these functions has been the task of synchronizing. The advantage of an automatic synchronizer at such a substation lies in the fact that a switch is closed the very first time that the frequency of the two systems to be tied together is within the synchronizing range. With manual synchronizing an operator may miss a number of good opportunities to tie the lines in while waiting for still better conditions. Loss of time from such delay is sometimes costly from the service standpoint. Installations of this kind have been made at six places on the system, two of these at generating stations. These installations are arranged so that an operator simply has to put in the synchronizing plug on the circuit to be synchronized. From this point the automatic synchronizer takes control, but at the same time, an indication of system conditions is given on the synchroscope and the operator is left free to use his communication system to give instructions regarding the frequency to the proper generating station.

In addition to the applications outlined above, there is, of course, a considerable number of installations of automatic synchronizers at completely automatic substations. At one of these substations a departure from standard practise has been made, and one synchronizing relay and one check synchronizer take care of synchronizing all the switches at the station.

Supervisory Equipment. The straight automatic station has had the most general application on the system dealt with, but there have been a number of cases where, because of the nearness of a substation to a dispatching point, supervisory control offered the best solution. As shown in Table I, four substations on the system have been provided for this type of control. The systems are of either the synchronous visual type, or of the synchronous selector type.

At Lima four 132-kv. oil circuit breakers and five 33-kv. motor-operated air break switches are controlled, and at Cherokee six 22-kv. and four 4-kv. breakers. Twelve 33-kv. oil circuit breakers and one 7,500-kva. automatic synchronous condenser are supervised at Bellefonte, and at Ivanhoe four 88-kv. and ten 13.2-kv. breakers are controlled. An illustration of the Ivanhoe Substation given in Fig. 16 shows clearly the substation development and the nature of the country in which it is situated.

Operating Experience

Beginning with the earliest automatic installations on the system and continuing from that time, care has been taken to follow closely the operation of each installation. A great deal of operating experience has, as a result, been gathered, covering both general experience with automatic applications and specific experience with automatic substation components. This is outlined below.

This procedure is responsible in a major degree for the uniformly successful operation of automatic equipments on this system.

General Experience with Automatic Applications

Reduction in Time of Outages. An automatic substation, when trouble occurs, will function in a minimum of time both to isolate the trouble and to restore normal conditions. The time of an outage to service is consequently reduced to an absolute minimum.

Reliability. The automatic substation is reliable both from the standpoint of mechanical reliability of its components and the reliability of its response to the

Fig. 16—The Ivanhoe Supervisory Control Substation

predetermined conditions for which it is designed to operate.

Automatic Versus Attended Substations. Since an automatic substation responds at once when a predetermined set of conditions obtain it is not subject to the errors of judgment to which even the best of operators are prone and this is a particularly important advantage in times of emergency. In one case, for example, while two of four ties between a large generating plant and a large city were out for maintenance, trouble occurred on one of the remaining ties leaving this load on a single line. This line had an automatic sectionalizing station on it. At this particular time an operator happened to be at this substation and when he noticed the indicating ammeters off scale he decided the line was in trouble and tripped it, causing the line breaker to lock out and resulting in a prolonged interruption. If left to the automatic equipment, this interruption would not have taken place.

Quality of Automatic Service. By its reliability, speed of action, and freedom from errors of judgment the automatic substation gives a brand of service which cannot be approached by even the best attended sub-

stations. This applies both to the service given to the feeders at a substation and to the service which the transmission system gives to the substation.

Reduction in Operating Expense. On the whole, the automatic substation is often less expensive to operate than an equivalent attended one. The increased investment cost with the automatic installation is frequently outweighed by the savings in the direct operating expenses of attendance and maintenance. Automatic equipment is designed to require a minimum of maintenance and when such work is necessary, it is carried out by men particularly well qualified and in the least amount of time.

Suitability of Automatics for Isolated Locations. It is difficult to obtain good operators for manual substations in isolated locations. Even if they are obtained, the isolation and lack of sufficient duties to keep them fully occupied usually results in a breakdown of their morale in varying degrees with consequent loss of efficiency. Automatic substations meet the requirements of such locations admirably.

Specific Experience with Automatic Substation Components

The closeness with which the operation of each automatic installation was followed soon showed up certain weaknesses and troubles with some of the component devices and apparatus. These are outlined briefly.

Relays. Plunger type relays provided with bellows for time delay and used on some of the early automatic stations were not adequate for the service. The bellows became stiff either from becoming too dry or because subjected to low temperatures, and this combined with the small air outlet greatly altered their time characteristics or made them inoperable. This led to their replacement at an early stage by induction type relays.

Contacts on many of the automatic relays were not sufficiently sturdy to handle repeatedly rated currents without considerable maintenance. More sturdy contacts with larger current carrying capacity had to be designed.

Motor Mechanisms. Trouble was experienced with motor mechanisms of the centrifugal type caused by binding of the operating links and clevises. A modification of the linkage system resulted in a trouble free design.

The latches of some of the early breaker mechanisms failed to hold when the motor had closed the breaker. A redesign of these latches eliminated this trouble also.

Motor-Operated Timers. A number of these devices on the early automatic equipments burned out because they did not have sufficient leeway in their voltage rating. They were redesigned for a normal rating of 230 volts with a tolerance of 30 volts above or below normal, which solved the problem.

Synchronizing Relays. These devices, though complicated have been remarkably free from trouble. About the only difficulty encountered was from high contact resistance because of too low an operating torque at synchronism. This was remedied by readjusting the shading pole pieces to increase the torque.

Energizing Transformers. The earlier automatic equipments used two distribution transformers on each incoming line for energizing the reverse power relays, for closing the breaker, and for providing reverse phase protection. As the use of automatic equipment was extended to the higher voltages, the cost of these components became a considerable factor in the cost of the equipment. It was finally decided to eliminate the second transformer on the incoming lines and install instead two transformers on the bus. Although this eliminated the reverse phase protection of the early installations, operating experience has justified the omission of such protection.

Tripping Batteries. At the first automatic substations 12-volt batteries were used for tripping. Difficulties were encountered because 12-volt trip coils required too much current and too much voltage was consumed in control wiring and contact resistance to leave a safe margin to operate the trip coil. Consequently, 24-volt batteries were substituted and trip coils developed to require less current for operation. At some substations where supervisory control is used, or where large apparatus has been automatized, 48-volt batteries have been employed. This has been done because some of the circuits at such substations include so many devices that their increased resistance makes the higher voltage necessary.

Conclusions

The authors believe that the history of the development and operation of automatic station equipment on the system they are associated with shows that certain conclusions can be drawn very definitely with regard to the effect of automatic applications to certain phases of electric power system development and operation. These are:

Flexibility and Adaptability of the Automatic Station and Contribution to Improvement of Service. The automatic station is one of the most flexible of tools which a system planner and designer has available. In the proper hands the automatic station in its various forms can be used with great benefit on almost any system; it is highly adaptable to any local conditions.

Reliability. The reliability of automatic equipment is at least as good as that of the very best type of operator. In general its reliability is better than that of the average operator, provided the equipment is reasonably maintained. Furthermore, automatic equipment will always repeat its performance. When it fails it will invariably leave a tell-tale mark behind it which makes possible the correction of the fault and eliminates the possibility of its recurrence. Many of our most efficient operators today prefer to leave certain functions to automatic equipment, *e. g.*, synchronizing, watching of bearing temperatures, etc. For carrying out definite

operations under infrequent emergencies automatic equipment is, too, as a general rule, more reliable than an operator.

Use at Isolated and Lonely Locations. Electric power system development frequently does not and cannot follow population centers. Switching stations may have to be located on lonely mountain sides or at points remote from any settled communities. The automatic station is the ideal solution for handling operating problems at all such locations.

Automatic Practise and System Cost. A great many data have been outlined in this paper to show the improvement to service which is possible by the application of automatic stations. Properly applied, however, automatic stations will not only improve service, but will do so at reduced cost. Reduction in the cost of the distribution end of electric service is one of the pressing problems of today. The automatic station application, in proper hands, is a tried tool and a sharp one for carrying out this particular job.

Universality of Application. Automatic practise is not only adaptable to switching stations, distribution stations, sectionalizing stations, etc., on power systems, but has been used in almost every branch of the power system. Its use has spread very successfully to such functions on power systems as coal handling, coal combustion, and frequency control. Other functions now handled on a manual basis will, with the development of the art of automatic practise be taken over by automatic equipments. There does not seem to be any reason to doubt that in the long run this will result in better service at lower cost, if the past experience in automatic practise is taken as a guide.

ACKNOWLEDGMENT

The authors wish to acknowledge the great help received from Mr. R. C. Miller in the preparation of this paper.

Discussion

A. E. Anderson: This paper readily indicates the extensive use that has been made of automatic switchgear on the system of the American Gas and Electric Company. The fact that over one hundred stations of different types are in use on this system permits the authors to obtain a wealth of operating experience and data. Most of the applications described in this paper are power line switching and distribution. However, the factors which enter here are, to a great extent, common to those found in other applications of automatic switchgear.

As stated by the authors, the first urge behind automatic switchgear was an economic one. In some cases it was possible to remove enough feeder copper to pay for a large share of the automatic control. Investments in automatic switchgear permit a reduction in operating costs and in this way meet one of the most important problems of the present time. With the increased reliability and speed over manual operation, together with other attendant developments, the economics of the situation are sometimes of secondary consideration. As a result of the experience gained with automatic switchgear, we now find that entire systems are being laid out for automatic operation. Such progress has been the result of well chosen applications, thoroughly designed control schemes and the careful selection of devices. In spite of these considerations, there still remains the important item of maintenance which is not expensive if well done and readily pays for itself. The items of inspection and maintenance were recognized from the beginning, and it was also realized that such functions should be performed by skilled employees. Devices form the heart of automatic control and must be suitably maintained if the desired character of service is to result.

Considering the extensive application of automatic switchgear on the system described in this paper; one is astonished by the relatively few cases of faulty operation on the part of the equipment. Some of these difficulties have been experienced in other installations as well, and action has been taken to eliminate these difficulties as fast as they occur. Time delay devices with oil dash pots or air bellows (with needle valves) were used in the early automatic stations. This was due to the fact that the choice of devices was limited to that used in manually operated stations. As the application of automatic equipment was extended it was found desirable to develop devices which would give more satisfactory operation. Oil dash pots and air bellows have been almost entirely eliminated by devices using motors, induction disks, escapement mechanisms, copper jacketed coils, etc., as the source of time delay. Only a relatively few devices using air bellows or oil dash pots remain in active production, and the application of such devices is limited to cases where the operating requirements are less severe.

Practically all devices used in automatic switchgear have a 10 per cent overvoltage rating. However, there have been cases where extensive regulation was obtained or other local conditions entered so as to cause the voltage to exceed 110 per cent normal for an appreciable length of time. Once the range is known, and it comes within the usual variation from maximum to minimum, it is possible to meet the requirements with available devices.

The late progress in the art confirms the decision that individual electrically-operated devices give the most flexible and least expensive arrangement.

An interesting comment is the absence of three-phase voltage check in the more recent installation, which action has been ustified from past operating experience. The increase in tripping battery voltage from 12 to 24 volts was found to leave a safer operating margin.

The writer feels that a standard a-c reclosing feeder is automatic in the sense as covered by definitions 26-50 and 26-53 of the Institute Standards. It is true that this type of equipment is not as elaborate as some machine equipments for example, in that it uses fewer devices and has less functions to perform. This, however, is due to the character of service afforded and is not a limitation of the equipment itself. A so-called standard reclosing feeder is:

a. Unattended in the usual installation.

b. Goes into operation by an automatic sequence under predetermined conditions.

c. Maintains the required character of service by automatic means.

d. Goes out of operation by an automatic sequence under other predetermined conditions.

e. Provides protection against all usual operating emergencies.

This paper brings out a number of valuable conclusions that are common to all forms of automatic switchgear. The more important of these conclusions are:

a. Reduced time of outage.

b. Not subject to errors in judgment.

c. Reliable in its operation. Results obtained are at least as good as those of the best type of operator.

d. Permits reduction in operating costs.

e. Applicable to isolated locations where it would be difficult to establish the desired type of operator.

f. Flexibility makes it readily adaptable to operating conditions.

g. Automatic switchgear is designed to require a minimum amount of maintenance which should be carried out by men particularly well qualified for this type of work.

Robert Treat: It has already been noted that in pursuing the paths of progress we sometimes find that a certain course of procedure results in a collateral and perhaps unexpected advantage which is more important or more valuable than the primary objective originally sought. In this connection the following verbatim quotations from the authors' paper are of interest. "The first urge behind the idea of automatic stations and substations was an economic one." "On the whole, the automatic substation is *often* less expensive to operate than an equivalent attended one." "By its reliability, speed of action, and freedom from errors of judgment, the automatic station gives a brand of service which cannot be approached by even the best attended substations." The authors found from experience that they *often* (presumably not always) achieved what was announced as the first urge behind the idea, but they put no such limitation on the improvement of service which resulted.

A further advance in the adaptation of automatic devices which is being introduced by a few operators lies in the automatic reclosure of circuit breakers instantly instead of after a time delay, as mentioned in the paper. Under certain conditions it has been found that breakers can be reclosed so promptly as to produce on the customer the impression that there was no interruption at all. It seems quite logical that such a procedure should secure quite widespread acceptance in the near future.

There is a tendency not only in the operation of electric substations, but apparently in all walks of life, to replace human effort which is expended in doing uniform repetitive tasks, with automatic machinery. We have already come a long way from the time when about the only automatic operation in a power station was performed by the speed governor. But there are still many tasks performed in power stations and substations which in the future will probably be taken from the operator. For example, one seldom visits a station without witnessing the operator making his half-hourly rounds taking meter readings to be added to the millions which he has already collected—for what purpose we sometimes wonder. May it not be that in the near future some genius will conceive a simple and inexpensive movie camera which can be permanently set up and trained on the entire switchboard; which automatically changes one frame and takes a picture of the board and all its instrument indications once every half-hour or other desired interval. Such records would at least have the merit of compactness.

Frequently it is not the values of voltage, current, kilowatts, etc., during normal steady system conditions in which we are most interested, but the values during a second or so of transient caused by a momentary abnormal condition. Here again the human operator is limited in performance because even if the instrument needles correctly followed the rapid changes in the measured magnitudes, the operator can hardly read even one, let alone the several in which we are interested. To supply this deficiency the automatic oscillograph has been developed. This constitutes still another tool for the further improvement of service.

Vibration and Fatigue in Electrical Conductors

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Associate, A.I.E.E. Associate, A.I.E.E. Associate, A.I.E.E.

Synopsis.—*This paper deals exclusively with the phenomenon "vibration." No reference is made to the allied phenomenon "dancing." The purpose of the paper is to stimulate further research in an endeavor to provide a fundamental preventive of vibration and the resulting fatigue. Economic features such as reducing tensions and spans, are not treated. Published information is referred to and the need of attacking the fundamentals causing vibration is investigated and demonstrated. Experiments using water as a medium on some special cable sections are described in detail. The paper shows that certain peculiar but not altogether impractical sections minimize the tendency of vibration and the resulting fatigue. The ideas underlying the design of these sections are discussed and conclusions drawn. Practical objections to these proposed cable sections are included. Further research is indicated.*

BECAUSE of a general increase in the unit working loads as well as in sizes of conductors, since about 1920, vibration has now become a problem for transmission organizations.

This very rapid vibration of overhead conductors (sometimes resulting in a musical note) was probably first reported, as deteriorating the mechanical characteristics of conductors, from California in 1923. These vibrations seldom have an amplitude exceeding two inches; the node lengths vary considerably and the frequency is of the order of 10 to 100 cycles per second.

Various organizations and interests, such as the State Electricity Commission of Victoria, Australia, the manufacturers of electrical conductors, and the electric utilities of Southern California, soon became interested in reports of these phenomena.

The need for fundamental preventives was made evident because of the following reports of results of vibration as found in the technical press. Bolts in towers became loosened and members were likely to become inoperative. Flat straps supporting arms of the towers seemed to vibrate on their own account. Insulator hardware has been damaged. In other cases, cables have had numerous strands cracked.

Remedial Measures

To overcome all these difficulties numerous mechanisms and appliances have been suggested and some of them function very well indeed. They are, however, always subject to the criticism that they may ultimately account for more harm than good. On the other hand, if the cause of the problem can be determined, and preventives applied at the source, there will then be little danger of the trouble showing up later at some unexpected point.

Bibliography of Vibration

A bibliography of the subject referring largely to cables and wires, and consisting of some 350 items, has been assembled, a large part of which was supplied by cable manufacturers, the American Society of Mechanical Engineers, and the Engineering Foundation. Of these, 65 articles were reviewed and studied. These articles may be divided into two sections, (1) those which deal with reinforcements, absorbers, and generally with curative measures; and (2) those which approach the problem from a fundamental standpoint, by determining the cause and proposing and reporting upon preventive measures.

Review of Investigational Work Done on Vibration in Cables

The more important researches were carried out by Relf and Ower, Karman, Shiba, Varney, Stockbridge, Thoma and Bate. Articles by Relf and Ower[1] and by Karman,[2] dealt with the theory of formation of eddies at the lee-side of stream flow and their relations to the periodicity of the resulting vibrations. Shiba of Japan has photographed the eddy formations, using smoke streams and a special camera taking 12,000 to 20,000 pictures per second by which the relation of eddy frequency to that of the vibrations might be more readily studied. Varney,[3] Stockbridge[4] and Bate[5] discussed various dampers, and generally put forward curative measures and absorbing devices.

Effects of Conductor Shapes

Following reports of a field observation from the Pacific Coast that a three-strand cable did not vibrate as heavily as a standard cable,[6] also that a single strand wrapped about a cable seemed to reduce the vibration,[7] it was thought, although a somewhat impractical cable cross-section might result, that some important principle might be involved which had not been investigated sufficiently. Again, there appeared to be an opportunity of providing fundamentally a preventive of vibration failure by modifying the section of the conductor rather than that afforded remedially by adding reinforcements and absorbers. Accordingly it was decided to make further studies of specially stranded and deformed cables.

Attention was soon called to Thoma's[8] findings, namely, that the section of the cable did play an important part in the vibration characteristics. It was thought that by upsetting the symmetry of the section, the eddies would be disrupted. This is explained in the following theory.

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Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

1. For references see Bibliography.

Ideas Governing the Design of Non-Symmetrical Sections

The successive cross-sections of a 5/8-in. diameter round rod with a 1/8-in. diameter wire spiralled about it, as shown in Fig. 1, have been selected to indicate the complicated system of frequencies brought about by the eddy formation at each of these successive cross-sections along the cable. Balancing of eddy forces is demonstrated at individual pairs of cross-sections. A 5/8-in. plain round rod is examined for comparison and it will be seen that there is no balancing action in this case. Examination of stream line flow was carried out by referring to photographs of somewhat similar cases as obtained by Shiba.

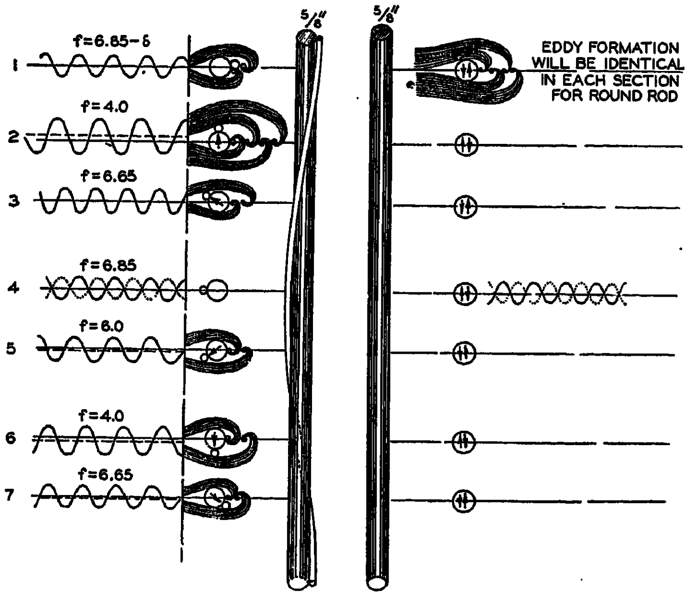

Fig. 1—Study of Eddy Formation in Lee of Uniform and Non-Uniform Specimens

Comparison of normal 5/8-in. round rod and 5/8-in. rod with 1/8-in. wire spiralled about it

$$\text{Frequency} = \frac{V}{D} \times \phi\left(\frac{VD}{e}\right)$$

Relf and Ower. Aeronautical Research Committee No. 825

Four variables which modify the resultant eddy action behind the rod and wire are introduced in each individual cross-section, namely:

(a) Frequency
(b) Phase
(c) Amplitude
(d) Neutral vibration plane

Each of these is studied in detail, as follows:

(a) Frequencies were calculated from the Relf and Ower formula. Assuming constant velocity of flow, the frequency is proportional to the diameter of the section. By varying this diameter, different frequencies will occur. In this case, variation is brought about by the spiralling of the wire about the rod. The effective diameter of the combination will be the diameter of the rod plus in cases such as sections 1, 2, 3, 5, 6, etc., Fig. 1, a percentage of the diameter of the wire. Only the diameters were considered in determining the frequencies and the theoretical curves were plotted from these values. These curves will then represent, to some scale, the actual frequency of the section.

(b) The phase of the vibration of an individual section will be governed by the position of the outer wire and has been plotted accordingly in the diagram.

(c) The force acting in the direction of vibration will be:

$$p = KV^2 \times D \text{ per ft. run per lb.}^5$$

Where P = force, V = velocity, D = diameter

Assuming velocity constant, the force will be proportional to the diameter. The amplitude of the vibration will, therefore, be proportional to the diameter. For each section in the diagram, the maximum amplitude has been plotted equal to the effective diameter and will, therefore, represent to scale the true amplitude.

(d) Vibration will take place about the center of impact of the section which will be offset from the horizontal diameter of the rod. This has been indicated by a broken line in the diagram.

The eddy formation and resulting forces have been plotted for an instantaneous position of the rod and will reverse at periods according to the frequencies involved, as indicated by the double arrows in the case of the round rod and double wave at cross-section No. 4, Fig. 1. No attempt has been made here to establish the exact mathematical value of the quantities involved. This is being investigated. The diagram illustrates the principle qualitatively, but not quantitatively.

It will be seen that at sections 3 and 7, and at 2 and 6, Fig. 1, the frequencies and amplitudes (therefore forces) are equal but are 180 deg. out of phase. They will, therefore, tend to balance one another in the direction of vibration, thus reducing this objectionable feature. In the case of the symmetrical round rod, the eddy formation will be identical at each section and no balancing tendency is evident.

At section 4, Fig. 1, of the combination of rod and wire, an unstable condition is introduced due to the fact that the forces on the sections on either side of it tend to move the conductor in opposite vertical directions.

It must be noted that this discussion deals with a very small length of cable—with 8 in. lay of the wire; the two boundary sections are separated 8 inches. Similarly, with three-strand cable the boundary sections would be separated by only two and two-third inches. In practise it is highly probable that over such a short section when compared with the length of the span, wind velocity would be approximately constant.

Special Sections Available for Study

The single wire spiralled about the rod is impracticable, on the application of tension, as the load on the

cable becomes eccentric. This analysis, however, points the way to modifying, in a practical way, the fundamentals of vibration in cables. For instance, in a three-strand cable, this same complication of frequencies would be introduced, but the tension would be uniformly balanced over the cable section. The four-strand cable is also a good example and is in common use, more especially in steel wire rope. Almost any

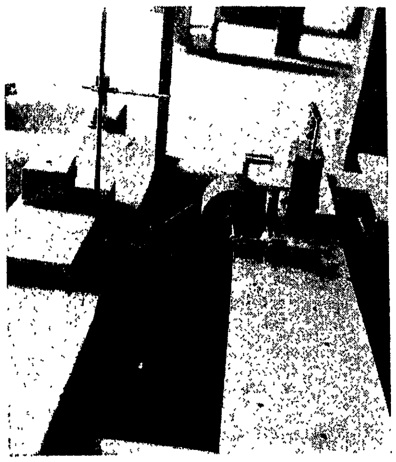

FIG. 2—SIDEVIEW OF APPARATUS USED IN RECORDING VIBRATIONS OF EXPERIMENTAL SPECIMENS IN WATER

sector or acorn shape may be made without much loss of mechanical strength by rolling or hammering the round cable as in insulated three-phase cables.

As a basis on which to work, it was decided to make sample specimens of sections of cables which were statically balanced so that they would not pull eccentrically. The section should, however, be unsymmetrical about the horizontal axis of the cable and at the same time be unsymmetrical for successive sections along the cable; or in other words, simulate those characteristics which seemed to interfere with vibration in the cable with extra wrapping referred to above. It was evident that as uniform an eddy action could not be expected over a length of these special cables, as appears to be the case with standard cables or round rod, with a consequent reduction of the power input from the wind.

LABORATORY WORK

Experimental work, based on these assumptions, was carried out in the Hydraulic Laboratory of the University of Toronto. Dr. Thoma's experiments and methods were followed quite closely. Water was used as a medium. The effect of change of shape on the amplitude of the vibration was sought. The specimen conductors of various peculiar shapes were tried at 5 different velocities of water. The range of velocities was from 4 to 7 inches per second. The sample was fastened to a flat steel strap one inch by one thirty-second inch and 5 ft. long, Fig. 2. This strap was used in preference to the elastic steel rod which Thoma used as it restricted movement in the direction of the flow of water most effectively. A light pointer was attached to the strap. This pointer traced the wave motion on a smoke chart, placed on the drum of a vibrograph.

The samples were divided into five groups. Each group had a circular sample as a standard and a number of irregular cross-section samples was compared with it. Projected dimensions, or effective diameters, of all the samples within each group were approximately the same, the object being to obtain the same frequencies of vibrations. In order that the vibrating system in each group should be as nearly as possible the same, the samples were made equal in weight and with centers of mass at the same point as that of the standard.

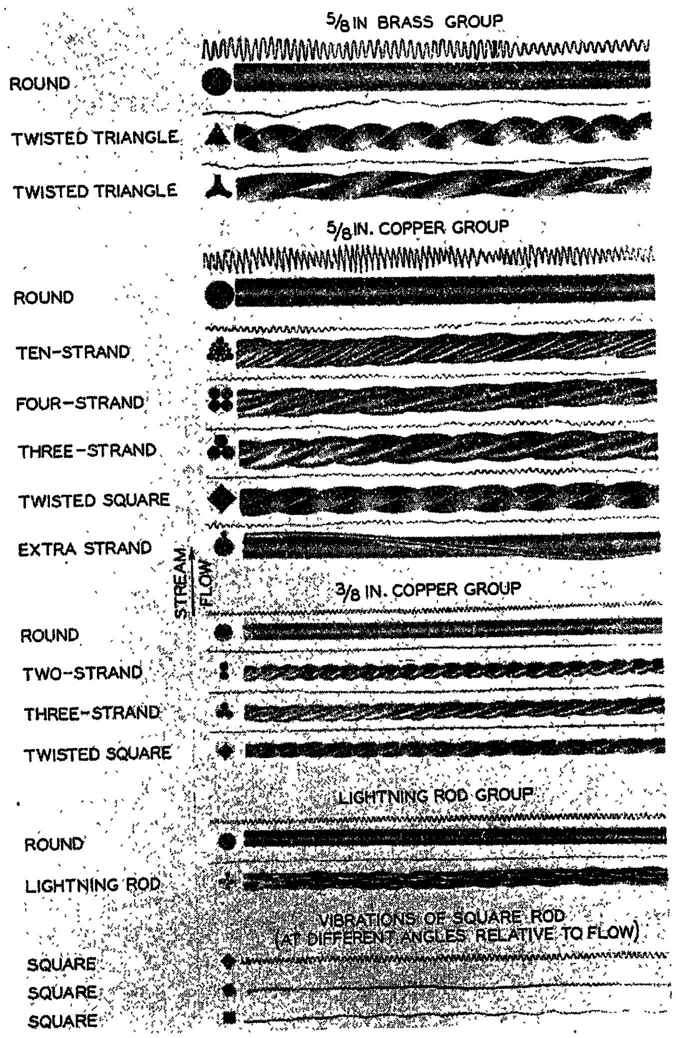

FIG. 3—VIBRATIONS IN WATER RECORDED COMPARATIVELY FOR VARIOUS SECTIONS AND TYPES OF CONDUCTOR

The adjustment for resonance was brought about by varying the length of the strap between the sample and the clamp till the maximum amplitude of vibration of the strap was obtained. Other sections in the corresponding group were similarly treated.

That the required similarity was obtained was evidenced by the fact that in each group adjustment for fundamental resonance of the various samples was

negligible and was seldom necessary at all so that the natural frequencies of the systems were approximately identical.

Owing to variations in speed of the smoke chart, no exact check could be kept on the observed frequencies, but the fact that no important adjustments were required within the groups leads to the inference that approximately identical frequencies were obtained in each case. In any case, the final purpose of the experiments was to derive qualitative rather than quantitative results. The design of specimens giving the same vibrating systems within each group (*i. e.*, the mechanical impedance) permitted the use of amplitude as a measure of the relative damping.

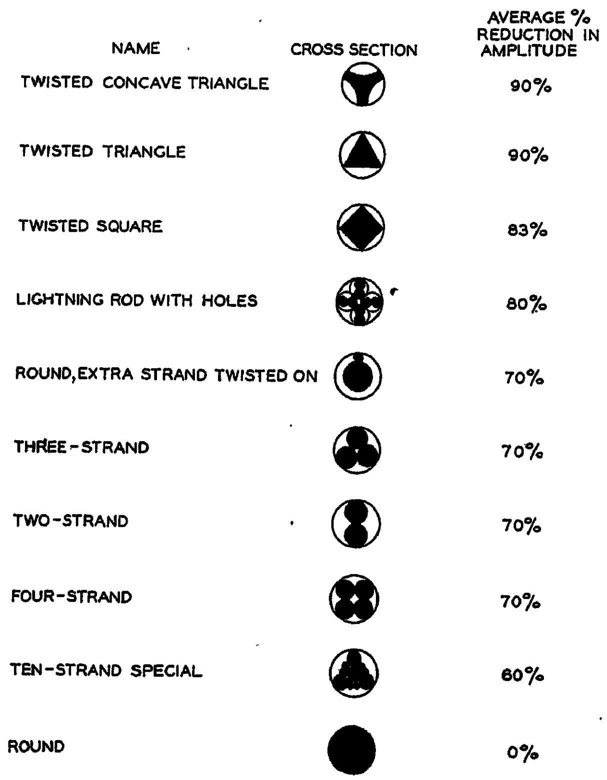

Fig. 4—Tabulation of Percentage Reductions of Vibrations as Observed in Water

List of shapes which reduce vibrations. Order of sequence: shapes giving maximum reduction lead the list

Conclusion Drawn from Hydraulic Experiments

Qualitatively the following conclusions may be drawn pending more practical experiments using air as a medium:

1. As evidenced by the charts, Fig. 3, it will be seen that so far as hydraulic experiments are concerned, the twisted triangular section overcomes most satisfactorily the tendency to vibrate.

2. It can be also noticed that practically all the sections tried, decreased the amplitude by at least 50 per cent when compared with the round rod, Fig. 4. From the results, it would seem advisable to construct a cable approximating in cross-section a triangle. Fig. 5 shows a series of cable sections derived from the basic sections which in the laboratory evidenced a considerable reduction in tendency to vibrate.

3. Even if these special triangular and rectangular sections prove impractical in cables, they may be used in outdoor buses where some difficulties of this nature may arise in future.

Later Steps in the Investigation of Vibration in Cables

1. At present special cables approximating triangular cross-sections have been made and are being strung in air to see how closely the hydraulic experiments are in agreement with the practical case. Three sections have been suggested; first, the ordinary three-strand cable which was casually observed in the West as being comparatively free from vibration; second, a nine-strand cable which is made up of 3 strands of three-strand cable with rope lay; and third, a special nine-strand cable using two sizes of strands, the three larger strands so placed in the outside layer as to give approximately the desirable triangular effect, Fig. 6.

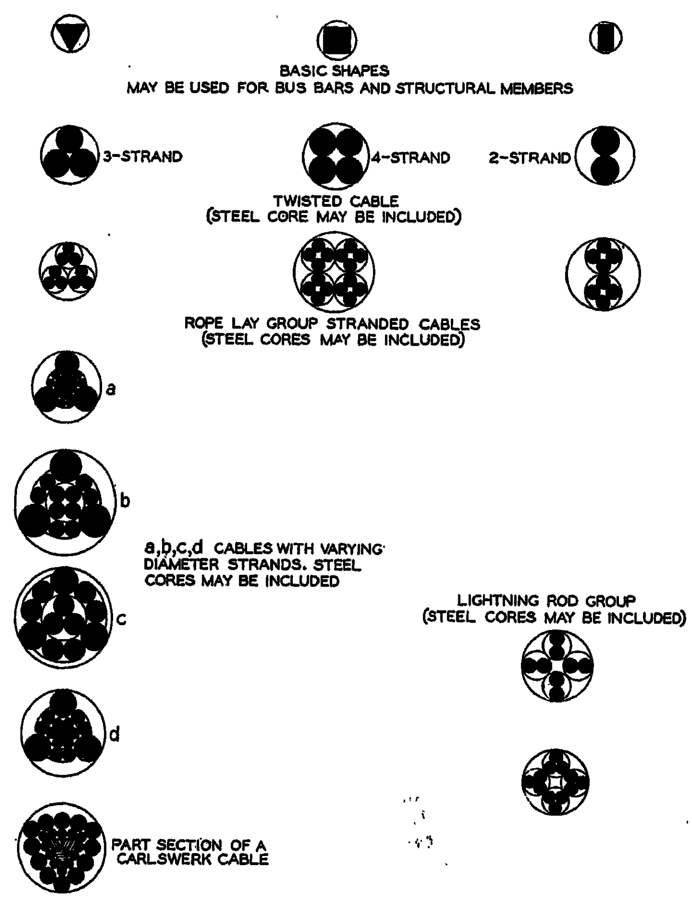

Fig. 5—Desirable Cross-Sections for Cables and Buses Which Are Exposed to Light Winds

Any combination of stranding, or grouping of strands of various diameters, which will approximate the basic shapes, *i.e.*, triangular, square, or rectangular, can be included in this set of cross-sections

The special rope lay cable introduces a feature which may be of great importance. Due to a characteristic of the stranding, air gaps, which will not collapse under tension, have been introduced. The presence of these air-gaps may serve to further upset the sequence of eddies behind the cable.

2. Acting conjointly with so-called "stiction" and "interstrand" friction, the elastic properties of the individual strands of a standard cable will tend to modify the vibration. Investigation should be made with the object of segregating these and to determine the comparative importance of the damping in each case. Does interstrand friction absorb any energy at all at the comparatively long radii of curvature found in vibration phenomena?

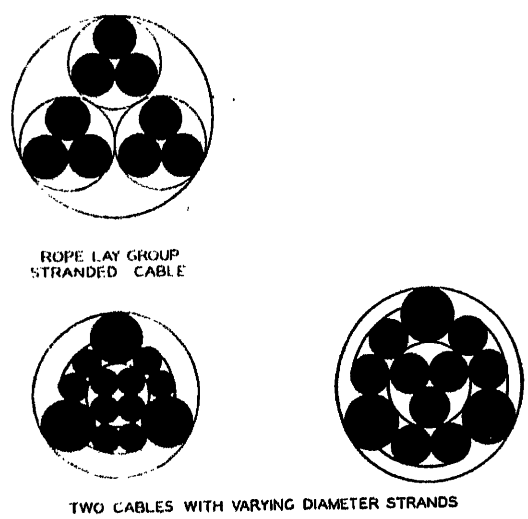

Fig. 6—Most Practical Cross-Sections for Suppression of Vibration

3. Experiments should be carried out to verify the following predictions which were made on two cables (6 by 0.2108; 7 by 0.0705, 266,800 cir. mils A.C.S.R., Owl, and 30 by 0.1059; 7 by 0.1059, 336,400 cir. mils A.C.S.R., Oriole). An attempt was made mathematically to predict the characteristic dimensions of vibration in these two cables and to balance energy input against energy dissipated, the remainder of the energy doing work on the cable at points of discontinuity, such as clamps. Many assumptions had to be made. Initial attempts at measurement in the field were unsatisfactory and this work was temporarily abandoned.

4. A determination of the actuating force per foot length of cable should be carried out. This could be done in a suitable wind-tunnel with adjustable elastic supports for the specimen under test.

Practical Difficulties

There are many objections to any departures from standard cables such as are indicated by these experiments. It is hoped that so far as vibration is concerned the proposed sections will indicate some new properties which in some cases at least will outweigh practical difficulties, such as standardization.

The corona loss may be increased to some extent. Also the increased diameters would account for greater wind pressures and sleet loadings. There would be some difficulty in making joints. Two sizes of strands in one cable would be a digression from the standards. If more than one pass through the stranding machine is required on account of these various sizes of strand, then the result would be increased cost.

Discussions and studies of these details are deferred until there is an opportunity to confirm in a practical way in air that the amplitudes of vibrations are suppressed.

Acknowledgments

Thanks are extended to Messrs. W. P. Dobson and W. B. Buchanan of the Laboratories of the Hydro-Electric Power Commission for cooperation in this work and for making several valuable suggestions.

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Four appendixes, including bibliography, have been assembled during experimental work and the preparation of this paper. They are available upon requests to the authors. They are,

A. Visualizing vibrations in small wires.
B. Bibliography.
C. Treatment of resonance by electrical analogies verifying laboratory method of investigation.
D. Mathematical investigation of vibration of 5/0 and 6/0 cables. (6 by 0.2108; 7 by 0.0705, 266,800 cir. mils A.C.S.R., Owl and 30 by 0.1059; 7 by 0.1059, 336,400 cir. mils A.C.S.R., Oriole).

Discussion

For discussion of this paper see page 1076.

Stress-Strain Studies of Transmission Line Conductors

BY G. W. STICKLEY*
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INTRODUCTION

THE actual tensile behavior of materials can be shown graphically by curves plotted from stress-strain tests, with stresses plotted as ordinates and strains (or extensions) as abscissas. Although it is recognized that stress-strain curves of stranded cables are appreciably different from those of single wires or rods, there is a comparatively small amount of information on this subject published in technical literature. With the advances being made in the solution of engineering problems, especially in the design of electrical transmission lines, these differences are becoming of increasing importance, and it is recognized that appreciable errors in design may result from neglect of them.

The purpose of this paper is to present the results of typical tensile stress-strain tests, illustrating the actual mechanical behavior of various types and kinds of cables

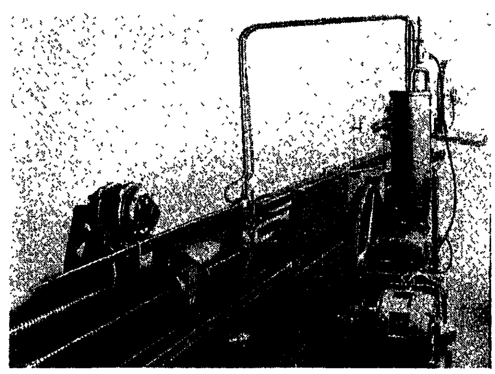

FIG. 1—100,000-LB. CAPACITY AMSLER CABLE TESTING MACHINE

used in overhead transmission lines, and also to present the results of similar tests illustrating the manner in which this behavior is affected by certain factors such as repeated stressing and lay.†

CABLE TESTING EQUIPMENT AND TEST PROCEDURE

Perhaps one reason that more information has not been published regarding the actual mechanical behavior of stranded conductors has been that most physical testing laboratories do not have suitable testing machines and accessory equipment. The fact that a cable is composed of a number of spiralled wires makes it necessary to use a long test sample in order to minimize the effects of any disturbance of strands during preparation

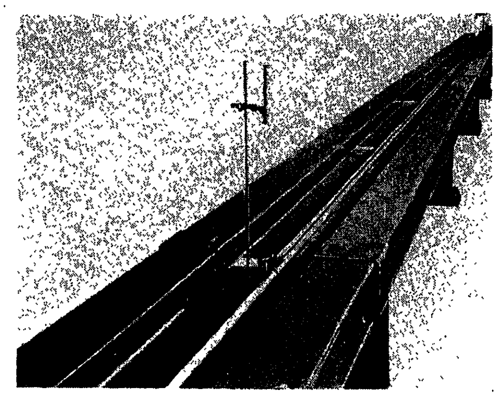

FIG. 2—CABLE SAMPLE READY FOR STRESS-STRAIN TEST

of the test sample and in order to obtain data which are representative of actual line spans of the material. For the same reason it is impractical to use the ordinary types of extensometers as in testing bar or sheet specimens.

The tensile tests of cable which are described in this article were made in an Amsler horizontal cable testing machine having four capacity ranges varying from 10,000 to 100,000 lb. and in which the samples tested

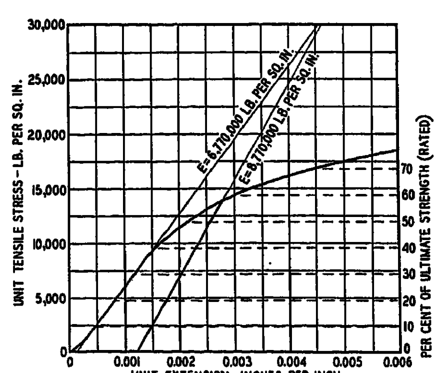

FIG. 3—REPEATED STRESS-STRAIN CURVES

266.800-cir. mil aluminum cable (7 × 0.1953 in.)

usually are 50 feet long. When making a stress-strain test the cable sample was suitably supported in a trough throughout the entire gage length in order to eliminate sag and to insure straightness of the sample at zero

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†The lay of a cable is the length expressed in inches for each complete turn of the wire around the axis, measured along its axis.

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stress. The elevation of the trough was such that when tension was applied the cable barely touched it. The apparatus used in obtaining the extension measurements consisted of telescopes mounted above steel scales fastened to the cable at each end of the gage length. Fig. 1 shows the testing machine, and Fig. 2 the trough, scales, and telescopes in place for making a stress-strain test.

Because one of the original reasons for making the stress-strain tests used as illustrations in this article was to show the behavior of transmission line cables both before and after loading, each test contained two stress cycles. In the first, the cable was stressed to some value equal to the highest maximum loading condition which might be used in design, this value varying from 50 to 70 per cent of the nominal ultimate strength. The stress then was removed, and in the second cycle the sample was stressed to a much higher value.

Results of Typical Tests of Various Cables

During the last several years tests as described in the preceding paragraphs have been made on more than eighty different sizes, types, and kinds of cable, including aluminum, aluminum alloy, copper, steel, A.C.S.R. (aluminum cable steel reinforced), and copperweld cables. Figs. 3 to 11 inclusive show typical repeated stress-strain curves which were obtained, and Table I contains average physical data from the tests of certain sizes and types of cable. Stress-strain curves of single wires from certain of these cables are shown in Figs. 12 and 13.

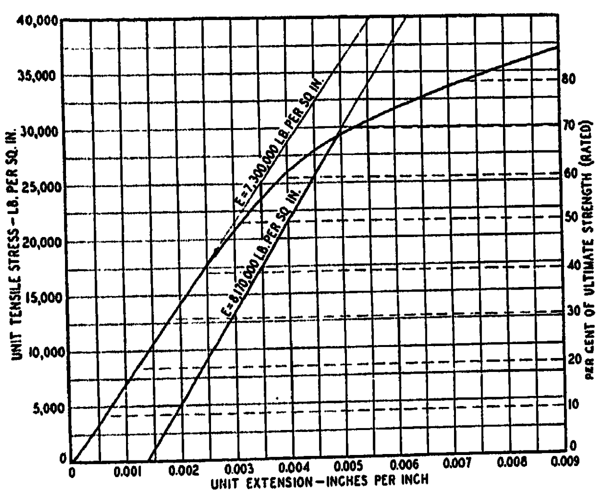

Fig. 4—Repeated Stress-Strain Curves

745,000-cir mil Aldrey (aluminum alloy) cable (61 × 0.1105 in.)

In Table I the theoretical values for the modulus of elasticity of aluminum, aluminum alloy, copper, and steel cables are the generally accepted values for these materials when in the form of bar, rod, or sheet. The corresponding values for the various types of A.C.S.R. are calculated from the theoretical modulus values for aluminum and steel and the proportionate cross-sections of the two metals in the respective cables. In the table there are two values for the actual modulus of each cable, the initial value being that which was obtained when the cable had not previously been stressed, and the permanent value the one after the cable had been stressed to from 50 to 70 per cent of its ultimate strength.

The fact that a cable is not perfectly elastic throughout the range of stress to which it may be subjected is overlooked frequently in calculating sags and tensions of transmission line conductors, and appreciable errors may result. As shown in some of the stress-strain curves included in this article, the base of the curve for the first stress cycle contains a small "foot" as a result of a small amount of unequal stressing of the individual wires, no doubt caused by a slight unavoidable looseness of the strands. The curves also show that the proportional limit is much lower than the stress at the assumed maximum loading condition, this in some cases occurring at a stress not greater than half of the latter value. As has been stated in a preceding paragraph, the assumed maximum loading condition frequently is from 50 to 70 per cent of the ultimate strength of the cable. Further examination of the stress-strain curves shows that application of some stress such as that equal to the assumed maximum loading condition eliminates the "foot" which originally occurred at low stresses and raises the proportional limit to a value near or equal to the stress applied.

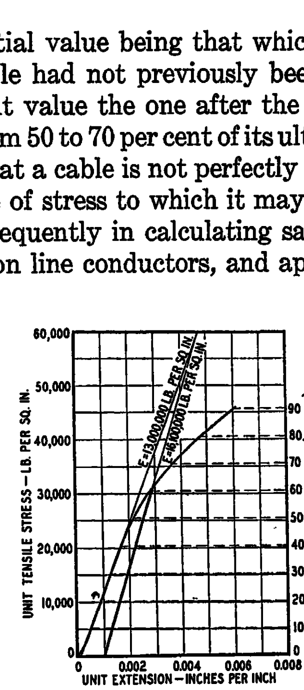

Fig. 5—Repeated Stress-Strain Curves

4/0 medium hard drawn copper cable (7 × 0.1739 in.)

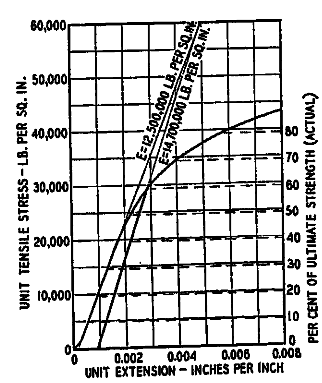

Fig. 6—Repeated Stress-Strain Curves

300,000-cir. mil medium hard drawn copper cable (19 × 0.1256 in.)

As will be noted in studying Table I, and in examining the stress-strain curves, the actual modulus of elasticity the first time that stress was applied to each cable was lower than that obtained the second time. The difference was less pronounced in cables composed of a small number of wires and in those made of high strength material. The first time that stress is applied it seems that the extension of the cable is not entirely the result of actual extension in length of the individual wires because of the tensile stress in them, but is partly caused by the individual wires being drawn more tightly in place. After this has once been done, all of the wires act more as a unit in the cable and the resulting modulus is higher.

As will be shown in several of the following paragraphs, tests have proved that the actual increase in modulus resulting from the application of stress depends, to a certain extent, on the value of stress applied, and that after a cable has once been stressed to a certain tension, the same load can be removed and applied again repeatedly without causing any additional change in modulus. In another paragraph it will be shown that coiling or otherwise disturbing a cable after its modulus has been increased by stressing to some tension will result in the modulus being lowered appreciably to some value usually greater than the initial value. This is considered evidence that the extension of a cable is not en-

TABLE I—MODULUS OF ELASTICITY OF SOME TRANSMISSION LINE CABLES

					Modulus of elasticity				
						Actual			
				Nominal ultimate strength		Initial		Permanent	
Kind of cable	Size -Cir. mil or No.	Diam. -In.	Stranding	-Lb.	Theoretical* Lb. per sq. in.	Lb. per sq. in.	% of theo.	Lb. per sq. in.	% of theo.
Aluminum	266,800	0.586	7 × 0.1953	5,030	10,000,000	6,770,000	67.7	8,770,000	87.7
Aluminum	300,000	0.628	19 × 0.1256	5,650	10,000,000	8,330,000	83.3	9,080,000	90.8
Aluminum	1,590,000	1.454	61 × 0.1615	30,000	10,000,000	6,000,000	60.0	8,350,000	83.5
Aluminum alloy	195,700	0.502	7 × 0.1672	6,550	10,000,000	8,420,000	84.2	9,250,000	92.5
Aluminum alloy	745,000	0.995	61 × 0.1105	24,935	10,000,000	7,300,000	73.0	8,170,000	81.7
M. H. D. copper	4/0	0.522	7 × 0.1739		16,000,000	13,000,000	81.2	16,100,000	100.6
M. H. D. copper	250,000	0.600	12 × 0.1443		16,000,000	10,300,000	64.4	13,700,000	85.6
M. H. D. copper	300,000	0.628	19 × 0.1256		16,000,000	12,500,000	78.1	14,700,000	91.9
M. H. D. copper	500,000	0.813	37 × 0.1162		16,000,000	9,450,000	59.1	13,200,000	82.5
Galvanized steel		0.364	7 × 0.1214	15,370	30,000,000	27,300,000	91.0	27,300,000	91.0
Galvanized steel		0.703	37 × 0.1004	55,600	30,000,000	25,400,000	84.6	26,100,000	87.0
A.C.S.R.	6	0.198	$\frac{6 \times 0.0661\ \text{Al}}{1 \times 0.0661\ \text{St}}$ (14.3% steel)	1,045	12,860,000	10,800,000	84.0	11,240,000	87.4
A.C.S.R.	101,800	0.276	$\frac{12 \times 0.0921\ \text{Al}}{7 \times 0.0921\ \text{St}}$ (36.8% steel)	9,365	17,370,000	14,450,000	83.2	15,550,000	89.5
A.C.S.R.	203,200	0.714	$\frac{16 \times 0.1127\ \text{Al}}{19 \times 0.0977\ \text{St}}$ (47.2% steel)	26,600	19,440,000	16,000,000	82.3	16,800,000	86.4
A.C.S.R.	4/0	0.563	$\frac{6 \times 0.1878\ \text{Al}}{1 \times 0.1878\ \text{St}}$ (14.3% steel)	8,435	12,860,000	8,890,000	69.1	11,260,000	87.6
A.C.S.R.	266,800	0.609	$\frac{18 \times 0.1217\ \text{Al}}{1 \times 0.1217\ \text{St}}$ (5.3% steel)	6,890	11,050,000	8,750,000	79.2	9,580,000	86.7
A.C.S.R.	266,800	0.633	$\frac{6 \times 0.2109\ \text{Al}}{7 \times 0.0703\ \text{St}}$ (11.5% steel)	9,385	12,300,000	10,000,000	81.3	11,260,000	91.6
A.C.S.R.	336,400	0.721	$\frac{26 \times 0.1138\ \text{Al}}{7 \times 0.0885\ \text{St}}$ (14.1% steel)	13,230	12,800,000	9,380,000	73.3	11,110,000	86.8
A.C.S.R.	378,800	1.074	$\frac{21 \times 0.1343\ \text{Al}}{37 \times 0.1151\ \text{St}}$ (56.4% steel)	70,700	21,300,000	16,650,000	78.2	17,000,000	79.8
A.C.S.R.	397,500	0.806	$\frac{30 \times 0.1151\ \text{Al}}{7 \times 0.1151\ \text{St}}$ (18.9% steel)	19,170	13,780,000	9,380,000	68.1	11,220,000	81.4
A.C.S.R.	795,000	1.093	$\frac{54 \times 0.1214\ \text{Al}}{7 \times 0.1214\ \text{St}}$ (11.5% steel)	27,950	12,300,000	8,110,000	66.0	10,100,000	82.1
A.C.S.R.	795,000	1.140	$\frac{30 \times 0.1628\ \text{Al}}{19 \times 0.0977\ \text{St}}$ (18.6% steel)	37,770	13,720,000	8,365,000	61.0	10,600,000	77.2
Standard tensile copperweld	3 No. 8	0.276	3 × 0.128		23,000,000	20,800,000	90.4	24,080,000	104.6
Standard tensile copperweld	3/8 in. (7 No. 8)	0.384	7 × 0.128		23,000,000	22,170,000	96.4	22,600,000	98.2
Xtra-hi-tensile copperweld	3 No. 8	0.276	3 × 0.128		23,000,000	22,470,000	97.7	23,200,000	100.8
Xtra-hi-tensile copperweld	3/8 in. (7 No. 8)	0.384	7 × 0.128		23,000,000	21,800,000	94.8	23,000,000	100.0

*Values for aluminum and aluminum alloy from *Aluminum Industry*, Vol. II; value for copper from *National Metals Handbook*; value for copperweld from Wire Tables, Copper Weld Steel Co.

tirely the result of actual extension in length of the individual wires, as explained in the preceding paragraph.

Comparisons of the modulus values in Figs. 12 and 13 with those in Figs. 3 and 8, respectively, show that even after increasing the modulus of elasticity of a cable by first applying some appreciable stress, the resulting value is less than the actual modulus of a representative wire from the cable, this difference in one case being as much as 12 per cent.

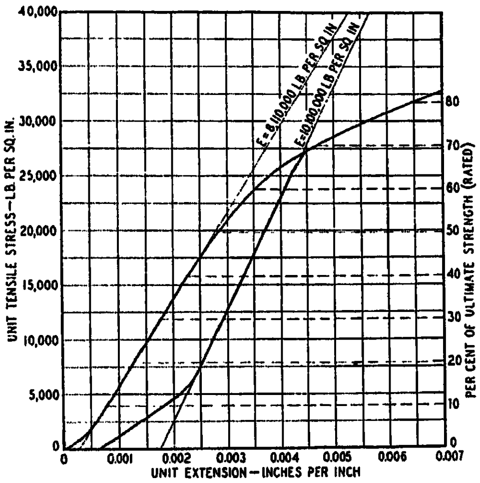

FIG. 7—REPEATED STRESS-STRAIN CURVES

795,000 cir. mil A.C.S.R. $\frac{54 \times 0.1214 \text{ in. aluminum}}{7 \times 0.1214 \text{ in. steel}}$

In addition to the errors resulting from the assumption that the modulus of elasticity of a cable is the same as that of a single wire, another source of errors is that of assuming incorrect values for the particular material being used. For example, a value commonly used for galvanized steel cables in transmission lines is 30,000,000 lb. per sq. in. The average modulus as determined in more than fifty tests of various sizes of galvanized steel wire varying from 0.0525 in. to 0.188 in. diameter, and in which a small stress had first been applied which straightened the wire, was 28,000,000 lb. per sq. in. Another example is the modulus of elasticity of aluminum, for which the values found in different handbooks vary from 9,000,000 to 11,000,000 lb. per sq. in. although the actual value, based on numerous tests of bar, rod, and sheet is 10,000,000 lb. per sq. in.*

Because A.C.S.R. is a composite cable made of aluminum and steel wires, some additional phenomena occur which are not found in tests of cable composed of a single material. As shown in Fig. 7, the part of the curve obtained in the second stress cycle contains a comparatively large "foot" at its base, which is caused by the difference in extension at the elastic limits of the aluminum and steel. In the curves shown in Fig. 12 the proportional limit, which for the purposes of this explanation may be considered practically the same as the elastic limit, is approximately 8,000 lb. per sq. in., the corresponding extension being 0.080 per cent. In the test of the steel wire, as shown in Fig. 13, the corresponding values are about 60,000 lb. per sq. in. and 0.215 per cent. When a sample of each of these two wires is gripped so that both will have to extend equal amounts, as when these two materials are used in A.C.S.R., a load which will produce a stress just equal to the 60,000 lb. per sq. in. in the steel will not give the steel any permanent set, but obviously will produce a pronounced permanent set in the aluminum. Then, if the stress is gradually removed, there will be a certain tension below which the steel wire will be carrying the entire load. In the test shown in Fig. 7 the stress applied during initial loading gave the aluminum wires a permanent set corresponding to the abscissa of the point at which there is a very definite change in direction of the straight sections of the curve in the second stress cycle (0.230 per cent), and gave the steel wires a permanent set corresponding to the distance from the origin to the base of the curve in the second stress cycle (0.070 per cent).

Fig. 9 is of interest because it contains an analysis showing the distribution of stress between the steel and aluminum wires in A.C.S.R., the analysis having been calculated from Figs. 7 and 8. As shown in Fig. 9 the actual unit stress in the steel core when the cable had not previously been stressed was never less than six times the corresponding actual unit stress in the aluminum wires.

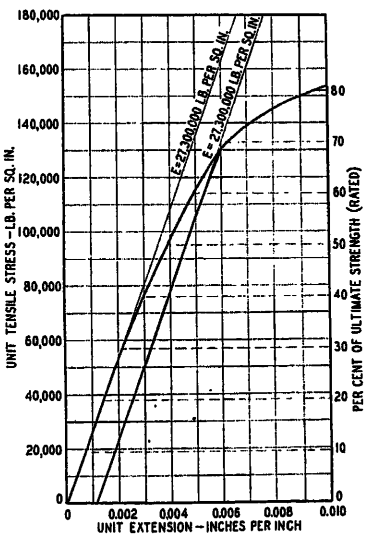

FIG. 8—REPEATED STRESS-STRAIN CURVES

Steel core of 795,000 cir. mil A.C.S.R. (7 × 0.1214 in.)

Most of this difference was the result of the difference in modulus of elasticity of the two materials, and the rest was caused by the "foot" which occurred at low stress in the initial part of the stress-strain curve. The analysis also shows that, because of the difference in extensions at the elastic limits of the two materials, as explained in the preceding paragraph, a different distribution of stress occurs after a stress greater than the elastic limit of the aluminum has been applied. In this

*The Aluminum Industry, Vol. II.

test the tension applied was such that when the cable stress subsequently was less than 6,500 lb. per sq. in. (approximately 15 per cent of the ultimate strength) the steel core was carrying all of the load.

Results of Tests Illustrating Effect of Several Factors

As has already been shown in this article, the application of stress of between 60 and 70 per cent of the nominal ultimate strength of a cable increases its actual modulus of elasticity materially. However, the actual increase depends on the magnitude of the stress applied,

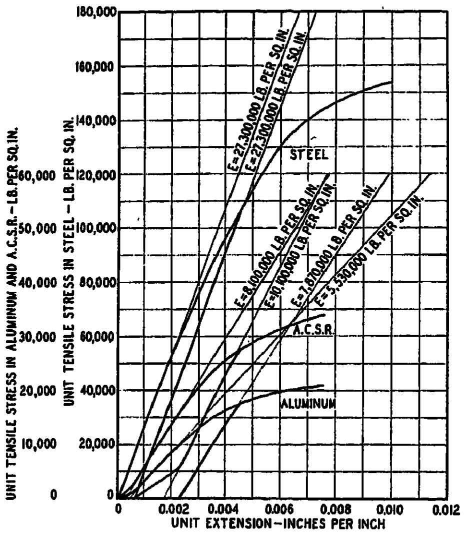

Fig. 9—Computed Stress-Strain Analysis

795,000 cir. mil A.C.S.R. $\frac{54 \times 0.1214 \text{ in. aluminum}}{7 \times 0.1214 \text{ in. steel}}$

the amount of increase becoming proportionately less as the value of stress used becomes larger. This seems logical because the first increments of stress applied naturally would produce most of the effect of drawing the individual wires of the cable more snugly in place.

Data from a test of 795,000 cir. mil A.C.S.R. (54 aluminum, 7 steel) which illustrate the increase in modulus resulting from certain values of maximum stress previously applied are included in the first part of Table II.

As stated in a preceding paragraph, tests have been made which prove that repeatedly stressing a cable to a

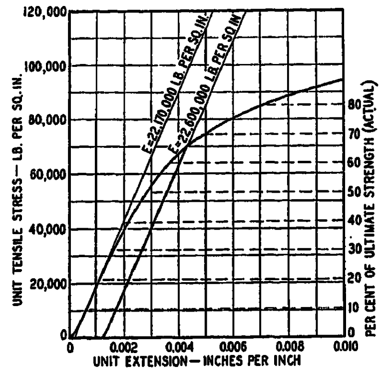

Fig. 10—Repeated Stress-Strain Curves

3/8-inch standard tensile copperweld cable (7 × 0.128 in.)

certain value does not cause any increase in the modulus of elasticity after that stress has once been applied. The latter part of Table II contains data from one of these tests which was made on some 266,800 cir. mil A.C.S.R. (24 aluminum, 7 steel) in which a stress equal to 66 per cent of the ultimate strength was applied and removed eight times, and was maintained constant at least 30 minutes each time before being removed. Although slight differences in modulus were obtained, the variation was not significant or definite.

Another factor which slightly affects the actual initial modulus of a cable is the diameter of the coil or of the reel drum around which the cable has been wrapped, the reason for this being that the cable is disturbed more by wrapping it around the smaller diameter. In tests of two samples of 795,000 cir. mil A.C.S.R. (30 aluminum, 19 steel) from the same length of cable but from inner and outer coils on the reel the modulus was 400,000 lb. per

TABLE II—MODULUS DETERMINATIONS—REPEATED STRESS-STRAIN TESTS OF A.C.S.R.

Cable size—cir. mil.	Stranding	Stress cycle	Max. stress previously applied—% of ultimate strength	Modulus of elasticity Lb./sq. in.	Modulus of elasticity % increase
795,000	$\frac{54 \times 0.1214 \text{ in. Al.}}{7 \times 0.1214 \text{ in. St.}}$	1	0	7,960,000	0
		2	38	9,320,000	17.1
		3	55	9,677,000	21.5
		4	69	9,820,000	23.4
		5	81	9,840,000	23.6
		6	86	9,840,000	23.6
266,800	$\frac{24 \times 0.1063 \text{ in. Al.}}{7 \times 0.0677 \text{ in. St.}}$	1	0	8,450,000	0
		2	66	10,200,000	20.7
		3	66	10,450,000	23.6
		4	66	10,350,000	22.5
		5	66	10,450,000	23.6
		6	66	10,200,000	22.5
		7	66	10,450,000	23.6
		8	66	10,450,000	23.6

sq. in. less for the former sample than for the latter, the respective coil diameters being 25 inch and 63 inch. This difference in modulus was 3.7 per cent.

As the length of lay of the wires of a cable is increased the cable tends to behave more as a bundle of parallel wires or a single wire. In other words, as the lay is in-

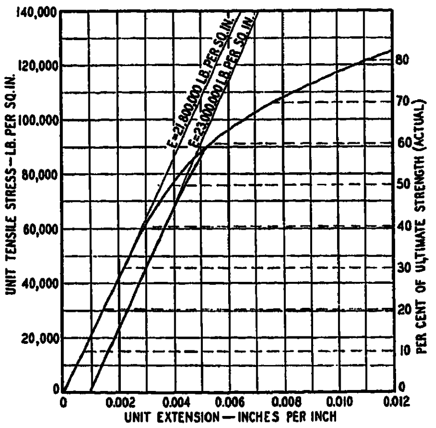

FIG. 11—REPEATED STRESS-STRAIN CURVES

3/8-inch xtra-hi-tensile copperweld cable (7 × 0.128 in.)

creased the actual modulus of the cable approaches the modulus of a single wire of the same metal or metals. This effect is illustrated in Fig. 14 which contains the stress-strain curves of three samples of 4/0 A.C.S.R. having different lengths of lay but made from the same original spools of wire. As would be expected these curves also show that the "foot" at the base of each curve was greatest for the cable having the shortest lay.

In the design of a composite cable such as A.C.S.R. consideration is given to this effect of lay upon modulus by stranding the steel core with the longest practical

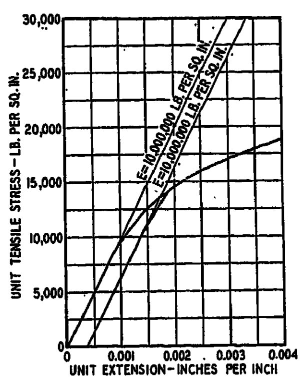

FIG. 12—REPEATED STRESS-STRAIN CURVES

Hard drawn aluminum wire—0.1953 in. (from 266,800 cir. mil aluminum cable)

lay and the aluminum wires with the shortest practical lay. By this procedure the core has a maximum modulus and the spiralled envelope of aluminum wires a minimum one, which results in the core carrying a maximum share, and the aluminum a minimum share, of the total stress in the cable. In the tests of the three samples of 4/0 A.C.S.R. discussed in the preceding paragraph the stress-strain curves for the aluminum envelopes were obtained in the same manner as was the similar curve in Fig. 9. The three curves are shown in Fig. 14, and as can readily be seen by comparing the stress in the aluminum envelope of each at a certain stress in the complete cable, there is an appreciable difference caused by the difference in lay.

An understanding of the mechanical behavior of cables from data such as presented in this article enables transmission line engineers to evaluate the effects of loading. Using this kind of data some engineers have designed lines in which during erection the conductors were stressed for several minutes to a tension equal to that which would result from their assumed maximum loading condition. One result of this procedure is that the cable is given its permanent modulus and its permanent set, and the stringing sag then is the permanent one, unless, of course, the assumed maximum loading

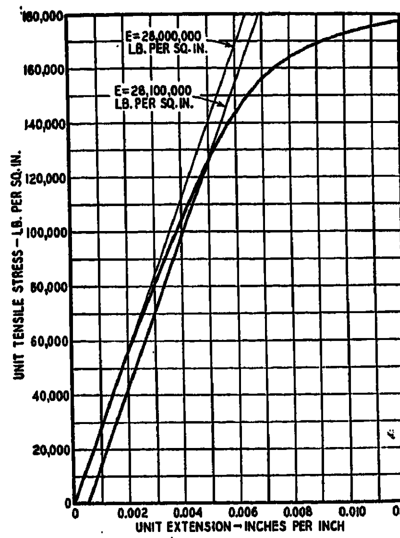

FIG. 13—REPEATED STRESS-STRAIN CURVES

Galvanized steel wire—0.1214 in. (from core of 795,000 cir. mil A.C.S.R.)

conditions are exceeded at some later time. It is evident that this treatment if otherwise feasible would make it unnecessary to take up the sag after a line is built, in order to maintain specified ground clearance.

Because of difficulties which usually arise in temporarily applying this maximum tension during the erection of a line, the feasibility of performing this operation using permanent equipment at the mill was investigated. However, stress-strain tests showed that winding the cable for shipment resulted in the loss of a large part of the effect which had been produced. Because of the handling and bending to which the cable is subjected when being wound on a reel, a certain amount of looseness of wires results. In two tests of A.C.S.R. which were made in order to illustrate this loss, the initial and permanent moduli of the first sample were determined. In the second test a stress equal approximately to 70 per cent of the ultimate strength was applied for 30 minutes,

the stress was removed, the cable was wound in a coil having a diameter twenty times that of the cable, and then the initial and permanent moduli of the sample after this treatment were determined. The two moduli values obtained in the test of the first sample were 8,350,000 and 10,000,000 lb. per sq. in. respectively, and the corresponding values in the second test were 8,750,000 and 9,850,000 lb. per sq. in.

CONCLUSIONS

The first part of this article describes typical stress-strain tests illustrating the actual mechanical behavior of various bare electrical transmission line conductors. From these tests and others which were discussed, the following conclusions seem evident:

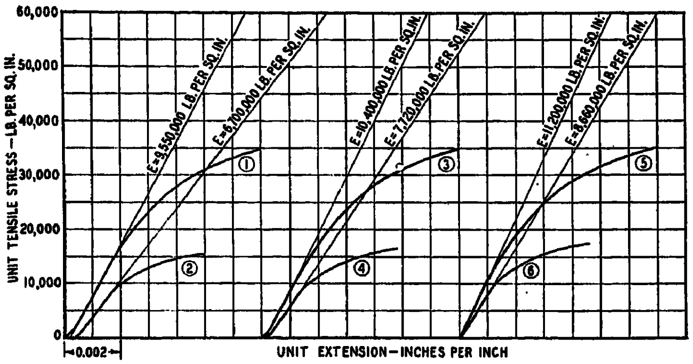

FIG. 14—REPEATED STRESS-STRAIN CURVES

Three samples of 4/0 A.C.S.R. $\frac{6 \times 0.1878 \text{ in. aluminum}}{1 \times 0.1878 \text{ in. steel}}$

NOS. 1 AND 2—A.C.S.R. AND ALUMINUM RESPECTIVELY
Length of lay 5 3/4 inches

NOS. 3 AND 4—A.C.S.R. AND ALUMINUM RESPECTIVELY
Length of lay 7 1/4 inches

NOS. 5 AND 6—A.C.S.R. AND ALUMINUM RESPECTIVELY
Length of lay 9 1/8 inches

1. Cables which have not previously been stressed are not elastic throughout the range of stress to which they ordinarily are subjected when used in transmission lines. The elastic limit usually is considerably less than the assumed maximum loading condition, and the actual extensions of a cable at low stresses are greater than those which would result from the elasticity of the solid material.

2. The proportional limit is raised by application of stress beyond this point. This also results in the cable then being perfectly elastic throughout all or most of the range of stress applied.

3. The application of stress to a cable also increases its actual modulus of elasticity. This increase depends to a certain extent on the magnitude of stress applied, the greatest increases occurring at the lower stress values. After the modulus has been increased in this way, the change is permanent and is not affected by the repeated application of the same stress. However, any considerable disturbance of the cable, such as that resulting from winding the cable on a reel, after having increased its modulus by application of stress, will decrease the modulus.

4. Because a cable is composed of a number of wires, its actual modulus of elasticity, even after being increased by stressing, is less than that of a single wire or rod of the same material.

5. The actual modulus of elasticity of a cable depends upon the lay of the individual wires, the longer the lay the more nearly the modulus becomes equal to that of solid material.

6. Although the temporary application of an initial stress equal to the maximum loading condition produces certain permanent conditions in the mechanical behavior of cables it is not advisable to do this at any place other than in the line during erection, because winding the cable on a reel, or any other handling after application of the stress, results in considerably decreasing the effects originally obtained.

ACKNOWLEDGMENTS

The tests described in this paper were made by the Physical Testing Division of the Aluminum Research Laboratories. This work is under the direction of Mr. R. L. Templin, Chief Engineer of Tests, Aluminum Company of America, and the tests were conducted under the immediate supervision of the writer. To Mr. M. E. Noyes, Aluminum Company of America, acknowledgment is due for his valuable suggestions.

Acknowledgment is also due to Allied Engineers who furnished some of the copper and copperweld cables used.

Discussion

For discussion of this paper see page 1076.

Vibration of Overhead Transmission Lines

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Non-member

INTRODUCTION

FAILURE of conductor strands from fatigue induced by vibration has occurred in widely separated locations throughout the world. Although but a small percentage of the total mileage has been affected, a study of the nature of the phenomenon and means of combating it is warranted.

Any suspended cable, irrespective of material, span length, tension, size, or character of supports will vibrate under certain conditions. This natural phenomenon has always occurred, but only in recent years has it been recognized as the cause of fatigue failures formerly described as crystallization.

About 1925 when the importance of vibration began to be appreciated, Aluminum Company of America started an investigation both in field and laboratory. The early results were presented to the Institute in two papers by Theodore Varney. In the first[4] a theory for the cause of vibration was presented which has received general acceptance, and in the second[5] reinforcement by armor rods was proposed as a means of protection. Recently a number of papers dealing with vibration has been published, particularly abroad.

This paper summarizes and interprets the results of laboratory and field work conducted by Aluminum Company of America since publication of Varney's papers.

Laboratory Work

The problem of eliminating vibration troubles involves the consideration of a number of factors. Determination of these factors demands a better understanding of (1) the actual stresses occurring in the conductors under field conditions; (2) the fatigue or endurance limits of the conductor materials; (3) the effects of various types of conductor accessories; and (4) practical means for minimizing the effects of or preventing harmful vibration. With these considerations in mind a large number of laboratory tests has been carried out during the past seven years, under conditions quite comparable to those in the field. While this work is by no means completed, so much progress has been made that the results obtained are of considerable interest to transmission engineers.

In the Vibration Laboratory at Massena, N. Y., large concrete piers are provided so that thirteen different spans of conductors may be tested simultaneously. The nominal length of each of these spans is 120 ft. Total tensions up to 20,000 lb. can be maintained on each specimen by means of suitable levers and weights. In addition to these, four 50-ft. spans are available for tests of single wires and the smaller stranded conductors. A general view of one wing of the laboratory, Fig. 1, shows some of the longer spans on the left and the four short spans on the right. A more recent installation of vibration equipment is shown in Figs. 2 and 3 where tests at higher frequency can be conducted. The frequencies used for single wires on the four shorter spans are still higher, sometimes being 7,000 per minute.

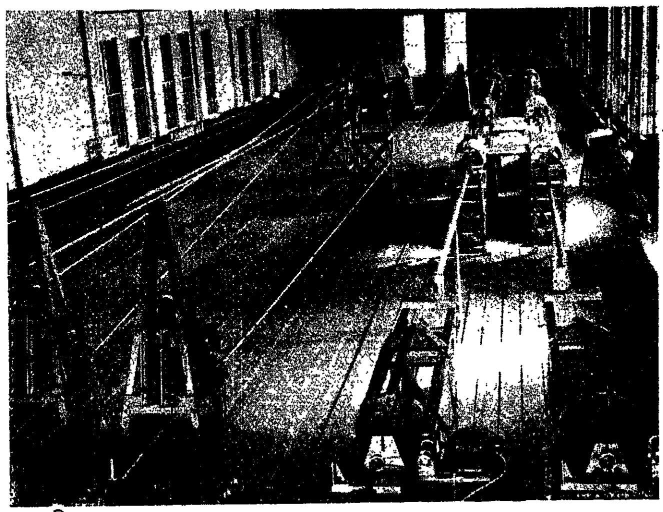

FIG. 1—VIEW OF ONE WING OF VIBRATION LABORATORY

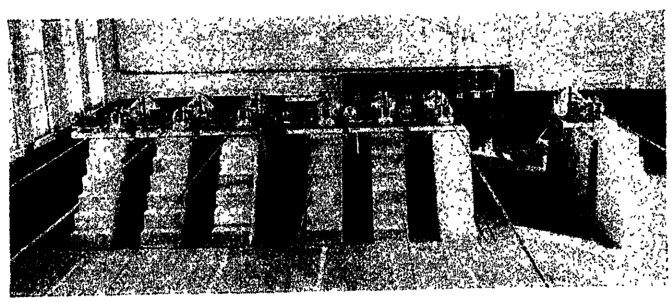

FIG. 2—FRONT VIEW OF VIBRATION APPARATUS

These higher frequencies are made possible by mounting an unbalanced flywheel directly on a specimen as shown in Fig. 4. The motion due to the unbalanced condition of the flywheel when rotating is restricted to the vertical plane only. The use of variable speed friction drives permits the use of constant speed motors. For such tests, however, it is necessary that the speed of the driving unit remain constant within very narrow limits. To accomplish this it was necessary to install a special inverted motor-generator set.

*Aluminum Company of America, Pittsburgh, Pa.

4. For references see Bibliography.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

Many of the vibration tests have been made primarily to determine the comparative life of various sizes of conductors under very severe conditions. A large mass of data is available but the summary results in Tables I and II for two sizes of A.C.S.R. are sufficient to illustrate a number of interesting facts. In the case of the 795,000 cir. mil A.C.S.R. vibrated in seven loops on 120 ft. span, each loop having an amplitude of 1⅛ in., the marked increase in number of cycles causing failure as the cable tension is decreased should be noted. By reducing the tension from 18,000 to 15,000 lb. the life of the cable is almost doubled for the conditions of vibration used. Similar increases occur with still lower tensions. The data in Table II for 397,500 cir. mil A.C.S.R., vibrated under somewhat different conditions, emphasize this same fact. Further consideration of the data indicates that the outer strands must be severely stressed. This is especially evident in the case of the tests made using the square faced clamps. The repeated bending imposed on these specimens irrespective of the tensions used was undoubtedly more severe than occurs in the field.

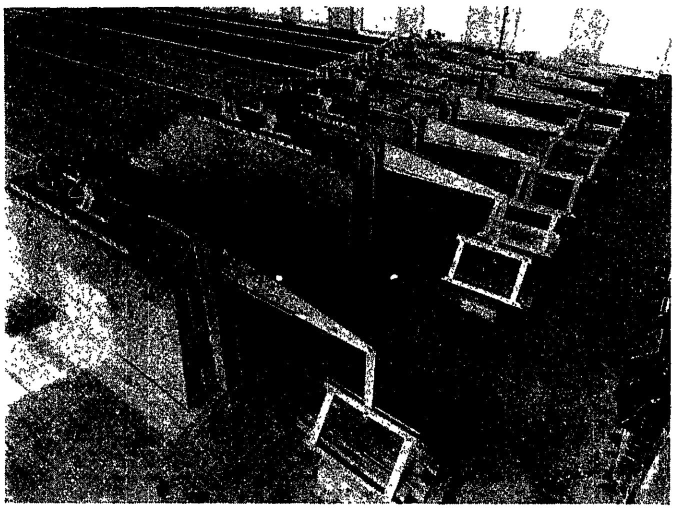

Fig. 3—View Showing Method of Loading Cables in Tension

Determination of Stresses

An adequate analysis of stresses in vibration conductors includes a consideration of the general phenomenon of vibration. The studies of such investigators as Varney,[4,5] Relf and Ower,[2] and Ryle[11] have certainly helped to a better understanding of this problem.

It is necessary to know the location and magnitude of the maximum stresses in any conductor under any given set of conditions to determine whether or not the fatigue limit of the material in the strands will be exceeded. If the stresses exceed the fatigue limits of the metals of which the conductor is composed and if the stresses are repeated many times, failure will occur eventually, the time depending upon the magnitude of the stresses.

The most direct method of evaluating the stresses in a cable under given conditions of vibration is by actual measurement. While at first thought this appears impossible because of limitations of available strain measuring apparatus, it has been found feasible by preparing and testing special large specimens, geometrically similar to those of usual size. So far two such specimens of seven-strand conductors have been fabricated and tested. One is a seven-strand hard drawn aluminum cable, each wire being 0.375 in. in diameter and possessing mechanical and electrical properties identical with those of standard conductors. The other is A.C.S.R. composed of six strands of the same wire stranded over a single steel wire. These specimens have been tested using a span of 120 ft. with various tensions and frequencies.

It was found that these specimens could be set in a very steady state of vibration and the position of the top and bottom of the cable at any desirable distance from the end support determined accurately by measuring with micrometer calipers the distance to suitable reference planes. The position of the cable for different test runs could be checked within a few thousandths of an inch, and from the measurements the deflection curve for the cable could be accurately determined when vibrating as well as when not vibrating. It is then comparatively easy to displace the cable under suitable static loads to the same extreme positions it took while vibrating. The strains measured with the cable in the deflected positions should correspond very closely with those in the cable during vibration. Fig. 5 shows a comparison between the measured and computed positions of the cable near the clamped end during vibration. The positions produced by static loading are so nearly identical that the differences cannot be shown in this figure.

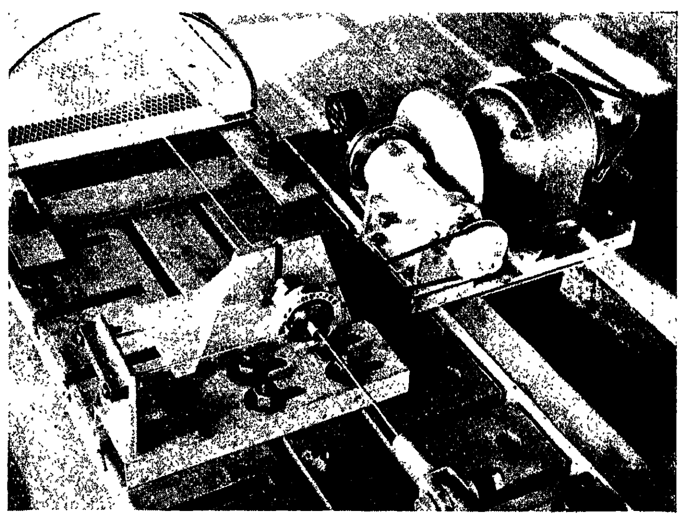

Fig. 4—Unbalanced Flywheel for High Frequency Vibration of Wires and Small Cables

By using specimens having such large strands it was possible to attach Huggenberger tensometers, using a ½-in. gage length, to the outside strands at various positions with respect to (1) the distance from the supports, (2) the circumferences of each strand, and (3) the circumference of the conductor as a whole. Fig. 6 shows two of the tensometers attached to a specimen for measuring strains at two particular points. Successive applications of load together with attachment of the tensometers at various points permitted a detailed

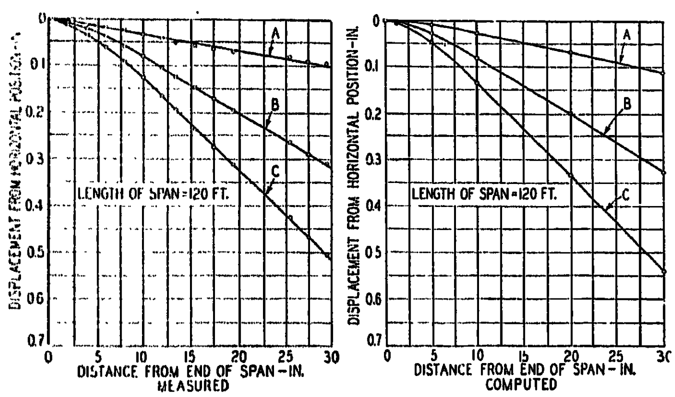

Fig. 5—Comparison of Measured and Computed Deflections of Cable

A—Upper position when displaced either statically or by vibration (7 loops—1⅛ in. amplitude)
B—Natural or free position of cable
C—Lower position of cable when displaced either statically or by vibrations (7 loops—1⅛ in. amplitude)

evaluation of the stresses (strains × modulus), occurring throughout the conductor. Fig. 7 shows a representative set of such data for three positions of the cable. Looking at a cross-section of the conductor from the support end, the top strand is numbered 1, then proceeding clockwise around the central strand, the other strands are numbered consecutively to six, the center strand being designated as 7. The conditions of the test are noted on the graph. The strains measured under static loading were further checked at the lower frequencies by reading the tensometers while the cable was vibrating.

Formulas for the general behavior of a vibrating cable have already been given in papers by Theodore Varney. The mathematical analysis which follows has been developed by R. G. Sturm of the Aluminum Research Laboratories. The frequency at which a cable will vibrate in a loop length, L, is equal to

$$f = \frac{6}{L}\sqrt{\frac{Tg}{W}} \tag{1}$$

where

f = frequency in cycles per sec.,
L = loop length or distance between node points in inches,
T = total tension in cable in lb.,
W = weight of cable in lb. per ft.,

and

g = acceleration due to gravity in ft. per sec. per sec.

Stresses from each of the following sources will be considered independently and the total stress taken as the sum:

1. The stress resulting from the direct tension in the cable.
2. The bending stress resulting from the static sag of the cable.
3. The bending stress resulting from the deformation of loops during vibration.
4. The increased tensile stress caused by the increase in length of the arc of the vibrating cable.

In order to facilitate following the steps in arriving at theoretical values of stress, each source of stress is considered separately.

1. The stress resulting from direct tension depends upon the ratio of steel to aluminum and to a certain degree upon the stranding of the cable. For a solid rod or for a cable in which the strands are all of the same metal this stress may be found by simply dividing the total load by the area of cross-section, *i. e.*,

$$S = \frac{T}{\text{area}} \tag{2}$$

If the cable is bimetallic the stresses in the different materials and the effect of stranding may be determined as outlined by G. W. Stickley.[16]

2. The bending stresses resulting from the weight of the cable will be practically negligible throughout the central portion of the span but might be quite severe in the immediate vicinity of the clamps. These stresses in general are neglected but in some transmission lines

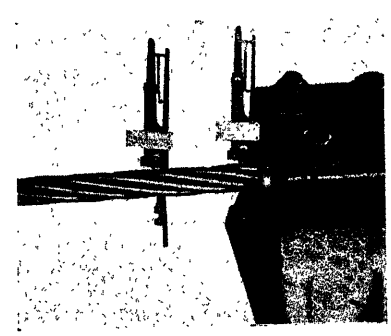

Fig. 6—Tensometers for Measuring Strains in Strands

they may be far from negligible. If the cable is clamped rigidly in a horizontal position at the end (which is probably a more severe condition than generally exists in actual service) the bending moment at the clamp may be expressed by the equation:

$$M_o = w \cdot \left(\frac{L_e}{2K} - \frac{EI}{T} \right), \tag{3}$$

where

M_o = bending moment at the clamp in in.-lb.,
w = weight of cable in lb. per in.,

L_s = span length of the cable in inches,

EI = flexural rigidity of the cable which depends upon the stranding conditions, but for a solid rod would be the modulus of elasticity times the moment of inertia of cross-section in lb.-in.[2],

T = total tension in the cable in lb.,

and

$$K = \sqrt{\frac{T}{EI}}.$$

The stress resulting from the bending moment, M_o, may be figured by the bending moment formula,

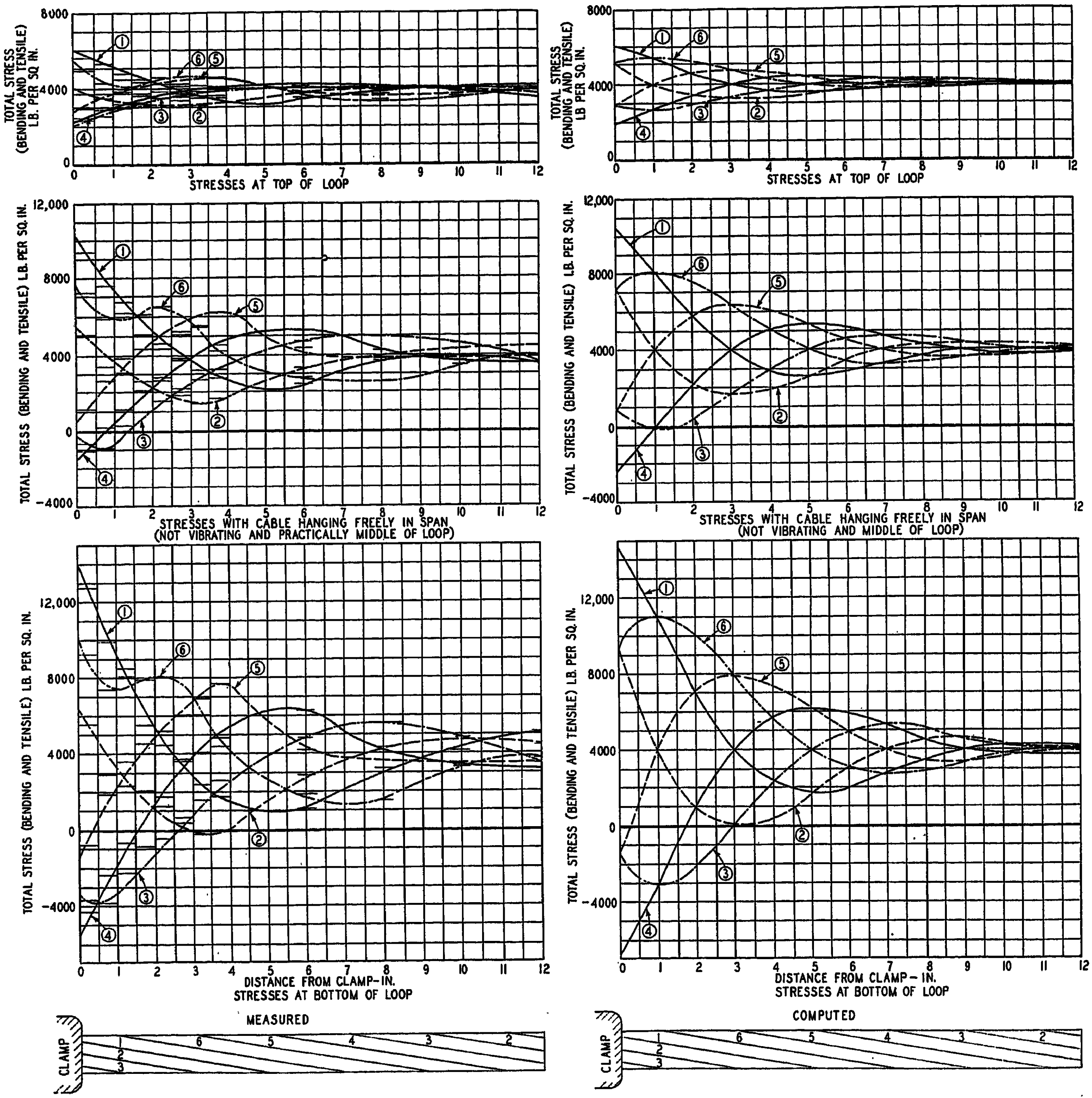

FIG. 7—DISTRIBUTION OF STRESS IN CABLE

Note: Cable tension 6,000 lb.
Tensile stress in aluminum 4,000 lb. per sq. in.
Length of span 120 ft.
Length of lay of cable 12 in.
Clamp at end of span square

The stress in the different strands of the cable at the position of top of loop and bottom of loop was determined for the cable deflected statically to the same position as when it was being vibrated in 7 loops and with $1\frac{1}{8}$ in. amplitude

$$S = \frac{M_o c E_o}{3\,EI}, \tag{4}$$

where

E_o = modulus of elasticity of the material in the outer strands in lb. per sq. in.,

EI = flexural rigidity of the cable in lb.-in.^{2},

and

c = half the outside diameter of the cable in inches.

The value of EI for a stranded cable can not be determined analytically because of the interplay of the strands upon one another. The effect of the stranding is not entirely independent of the tension applied to the cable and, therefore, must be determined for the average working tensions under which the cable will be used.

In order to determine the values of EI for stranded cables, load-deflection tests were made on the center section of a long cable. A span length of at least six times the lay of the cable was chosen in the center portion of the span. Supports were blocked up under the cable and the cable clamped to the supports after the tension had been applied. (See Fig. 8.) Transverse load was then applied to the midpoint of this secondary span and deflection readings taken for increments of load. The ordinary beam formulas for determining these deflections no longer hold because of the relatively large direct stress in the member. Setting up the differential equation representing equilibrium and continuity in the beam, it is found, however, that

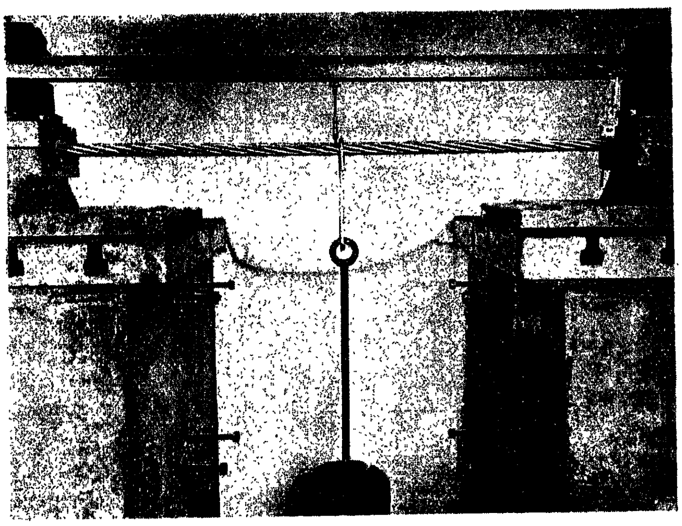

FIG. 8—SHOWING METHOD USED TO DETERMINE EI VALUE OF CABLES

$$\frac{d^2y}{dx^2} - \frac{T}{EI}\,y = \frac{M_o}{EI} - \frac{PL}{4\,EI} + \frac{Px}{2\,EI}, \tag{5}$$

where

P = load at the center of the intermediate span in lb.,

y = deflection in the direction of the load in inches,

x = distance from the left end of the intermediate span in inches,

and the other terms are as previously defined.

A solution of this equation gives not only the shape of the deflected cable but also the equation for bending moment at every point in the cable since

$$M = EI\,\frac{d^2y}{dx^2} \tag{6}$$

The boundary conditions that must be satisfied are that the deflection at the clamped ends is zero, that the slope at the clamped end is zero, and the slope at the middle of the span is zero. The resulting solution gives

$$y = \frac{P}{2\,KT\left(e^{\frac{-KL}{2}} + 1\right)}\left[-e^{-Kx} + e^{-K\left(\frac{L}{2} - x\right)} - 1 + e^{\frac{-KL}{2}}\right] + \frac{PL}{4\,T} - \frac{Px}{2\,T}, \tag{7}$$

and the maximum deflection at the center is

$$y_m = \delta = \frac{P}{KT}\left[\frac{KL}{4} - \frac{1 - e^{\frac{-KL}{2}}}{1 + e^{\frac{-KL}{2}}}\right] \tag{8}$$

Knowing the load, P, at the midspan, the tension, T, on the cable and the deflection, δ, for any given span length, it is possible to find the corresponding value of K and from this the value of EI for the cable. The values of EI thus obtained may be tabulated for use in the stress formulas.

3. The stresses at the clamped ends or points of support caused by vibration may be computed on the basis of the static conditions which will produce a deformation of the cable identical with that occurring during vibration. It may be shown that the deflection of a span of length, L, (the loop length) loaded with a load, P_1, which will give a deflection equal to 0.7 times the amplitude will give the conformation desired at the clamped end. From the equation

$$\delta = \frac{P_1}{KT}\left[\frac{KL}{4} - \frac{1 - e^{\frac{-KL}{2}}}{1 + e^{\frac{-KL}{2}}}\right], \tag{9}$$

the value of P_1 which will give a deflection, δ, equal to 0.7 of the amplitude is first found. Then the bending moment at the edge of the clamp may be computed from the formula

$$M_o = \frac{P_1}{2\,K} \cdot \frac{1 - e^{\frac{-KL}{2}}}{1 + e^{\frac{-KL}{2}}} \tag{10}$$

where the terms are as previously defined. The stress resulting from this bending moment may be computed

by means of equation (4). It should be noted that this stress is oscillating and produces equal stress components in opposite directions on top and bottom, both being subjected to alternate tension and compression. The stresses throughout the length of cable resulting from the bending during vibration may be computed from the formula

$$S = \frac{1}{2}\pi^2 E_o \cdot \frac{c}{L} \cdot \frac{A}{L} \qquad (11)$$

where A = amplitude of vibration in inches, and the other terms are as previously defined.

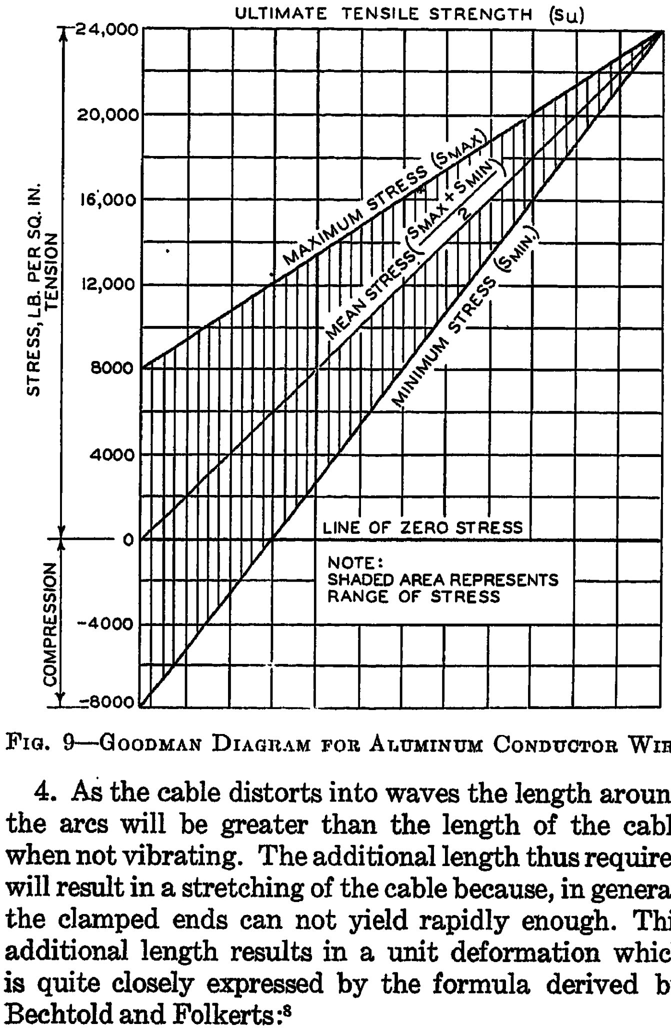

Fig. 9—Goodman Diagram for Aluminum Conductor Wire

4. As the cable distorts into waves the length around the arcs will be greater than the length of the cable when not vibrating. The additional length thus required will result in a stretching of the cable because, in general, the clamped ends can not yield rapidly enough. This additional length results in a unit deformation which is quite closely expressed by the formula derived by Bechtold and Folkerts:[8]

$$\epsilon_s = \frac{8}{3} \cdot \frac{A^2}{L^2}, \qquad (12)$$

where ϵ_s = unit elongation of the cable, and the other terms are as previously defined.

The resulting stress then may be computed as

$$S = \frac{8}{3} E_o \cdot \frac{A^2}{L^2} \qquad (13)$$

in which E_o = modulus of the cable as a whole.

This stress is simply an increase in tension of the cable which in general is quite small but which may not be negligible in many cases.

By proper combination of all of these stresses the total stresses in the vibrating cable may be computed to a fair degree of accuracy. Fig. 7 shows the stresses actually measured in the cable and those computed on the above basis.

It may be noted that the stresses measured on the top part of the cable, *i.e.*, where tensile stresses are great, are slightly lower than the theoretical stresses, whereas on the under side of the cable, where compressive stresses exist, the actual measured stresses are somewhat greater than the computed stresses. This is due to the fact that the tensile stress tends to pull the strands closer together, whereas the compressive stress causes them to push out, tending to move the neutral axis toward the top.

It has been found quite feasible to measure with suitable accuracy the deflection curves and determine EI values for all sizes of commercial conductors. Following the general procedure just outlined measurements of stress can be made on the smaller sizes of cable. This work is now in progress and the limited results obtained to date indicate that the theoretical analysis may be accepted with considerable assurance.

In applying this study to transmission line problems it is important to remember that no allowance has been made here for relief of stresses by sympathetic motion of

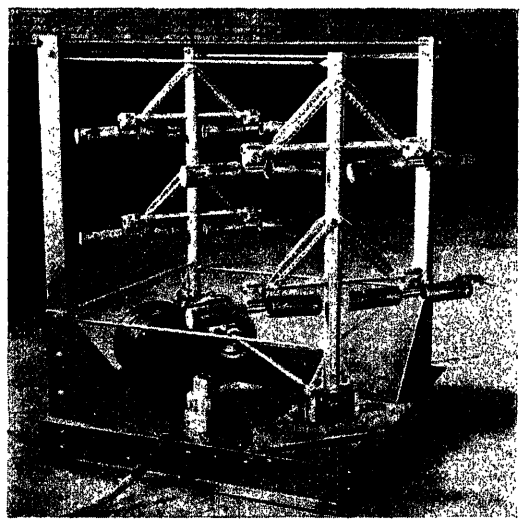

Fig. 10—Vibration Damper Fatigue Testing Machine

the supports of the cable. The supports used for tests were practically rigid. Supporting clamps and insulator ties used on actual transmission lines are far from rigid.

Fatigue Properties of Materials

Assuming that the limits of the stress ranges for the critical section in a cable can be determined, it is desirable to know the safe limits of the stress ranges for the materials in the cable. This information is best obtained from vibration tests of single wires under various known conditions. Such tests are essentially fatigue tests in which both the mean stress and the

stress ranges may be varied throughout wide ranges. Tests show that when the mean stress is zero the endurance limit based on 500 million complete reversals is 8,000 lb. per sq. in. for hard drawn aluminum conductor metal. Using this value and the Goodman diagram which, although not checked very thoroughly by experimental data, has been found to give safe values, we obtain the limiting ranges of stress shown by Fig. 9. This shows that as the mean stress increases from zero to the ultimate strength of the material (24,000 lb. per sq. in.), the safe range of stress decreases from 16,000 lb. per sq. in. to zero at the ultimate strength. Tests on single wires are now in progress for the purpose of checking the Goodman diagram both for hard drawn aluminum and steel but because of practical difficulties in carrying out the tests, results are being obtained rather slowly. Experience has shown that with single wires vibrating at high speeds it is extremely difficult to maintain uniform vibration. Recent improvements in testing apparatus, however, indicate that the major troubles have been overcome.

Effects of Conductor Accessories

Many tests have been made for the purpose of determining effects of various types of fittings on the vibration or fatigue life of electrical conductors. Space limitations prevent inclusion of all results in this paper.

Armor Rods and Vibration Dampers

The effects of bell-mouth clamps in increasing the life of vibrating cable is well illustrated in Tables I and II where the number of cycles for failure is shown for cable with square clamps and with bell-mouth clamps. It will be noted that the life of the cable has been practically doubled in every case. This is explained by the fact that the bell-mouth clamp prevents the severe concentration of stress that occurs at the square clamp.

TABLE I—SUMMARY OF VIBRATION TESTS

795,000 cir. mils A.C.S.R. $\left(\frac{54 \times 0.1214 \text{ in. aluminum}}{7 \times 0.1214 \text{ in. steel}}\right)$

Span: 120 ft. No. of loops: 7. Amplitude: 1-1/8 in.

Cable tension, lb.	Cycles for first failure of a strand in the cable: Square clamp	Bell-mouth clamp	Bell-mouth clamp with armor rods
18,000	433,000	1,148,000	24,000,000
15,000	796,000	2,078,000	40,538,000
10,000	1,166,000	6,242,000	95,400,000*
7,000	9,770,000	16,211,000	110,700,000*
5,000		75,200,000*	84,900,000*

*Still running.

If armor rods are used with bell-mouth clamps the life of the cable is increased many times, as illustrated in Tables I and II. While these tests have not been completed they have run long enough to demonstrate the effectiveness of armor rods as a means of overcoming vibration troubles.

TABLE II—SUMMARY OF VIBRATION TESTS

397,500 cir. mils A.C.S.R. $\left(\frac{30 \times 0.1151 \text{ in. aluminum}}{7 \times 0.1151 \text{ in. steel}}\right)$

Span: 120 ft. No. of Loops: 14 Amplitude: 9/16 in.

Cable tension, lb.	Cycles for first failure of a strand in the cable: Square clamp	Bell-mouth clamp	Bell mouth clamp with armor rods
7,000	3,775,000	11,289,000	49,910,000
5,000		26,380,000	176,100,000*
4,000	45,316,000	106,210,000	377,000,000*

*Still running.

It is possible by means of dampers to practically eliminate the vibration of a cable. The laboratory work on vibration dampers has included extensive tests to determine the relative life of various dampers of the Stockbridge type using the special fatigue testing machine shown in Fig. 10. The machine can be operated at various speeds from about 600 to 1,020 r.p.m. using any amplitude from zero to ½ inch. Provision is made

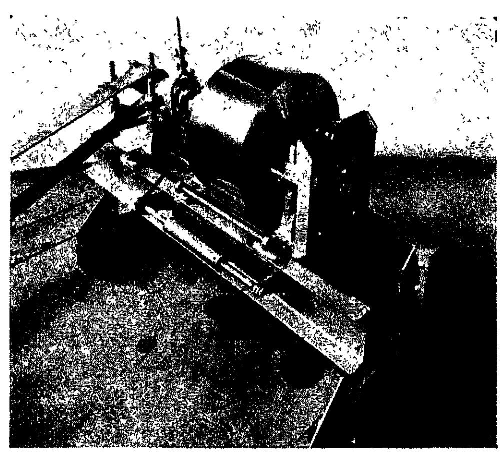

FIG. 11—VIBRATION DAMPER EFFICIENCY MACHINE

to test 8 dampers simultaneously. Tests with this machine permit the selection of proper cable for supporting the weights and assist in refinements of design.

The special testing machine shown in Fig. 11 was intended to measure the efficiency of various types and sizes of vibration dampers by measuring the rate of deceleration of the flywheel after it and the attached damper were brought to a definite high speed and then disconnected from the motor. So far the test data have not been satisfactory for determining the efficiency of dampers but the machine has given valuable information relative to critical frequencies of dampers.

Dampers of the Stockbridge type have two critical speeds or natural frequencies which are dependent upon the material, size, length and stranding of the damper cable as well as the size, shape and method of attachment of the weights. The computed frequencies have been found to agree with the observed frequencies within the limits of experimental error. The amplitude

of oscillation of the damper weights for any given forced vibration of the center clip depends upon the frequency of the forced vibration and the damping characteristics of the damper cable.

Knowing the damping characteristics of the damper cable this amplitude may be computed and from that the energy absorbed per cycle or per second. This value together with the forces developed by the vibrating weights will give criteria for selecting the most suitable damper for any given conditions. Limitations of space will not permit giving the mathematical analysis.

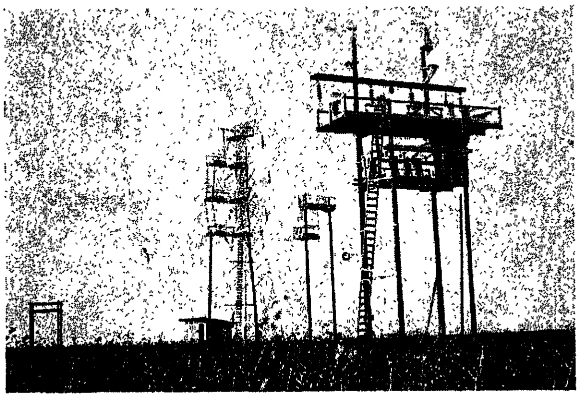

FIG. 12—OBSERVATION STRUCTURES, ROYSE CITY EXPERIMENT STATION

Field Work

Laboratory research has been coordinated with field observations on operating lines in various locations. Early in 1930 it was decided to establish a field laboratory equipped for accurate study. The station was established near Royse City, Texas, about 35 miles east of Dallas. Chief among the considerations which led to this selection were the flat unobstructed topography and the remarkably steady wind conditions. A vacant position on an existing steel tower line was made available for experimental work by the Texas Power and Light Company and additional spans nearly at a right angle to the existing line were erected on wood H-frames. This site has proven to be excellent, since hardly a day has passed without vigorous vibration being recorded on at least one of the two test lines.

In addition to the field studies at Royse City, observations have been conducted on operating lines as follows:

The Public Service Electric and Gas Company of New Jersey on the 795,000-cir. mil A.C.S.R. conductor and 203,000-cir. mil A.C.S.R. ground wire of the 220-kv. Roseland-Bushkill Line.

The Pennsylvania Power and Light Company on the 184,000-cir. mil ground wire of the 220-kv. Plymouth Meeting-Siegfried Line.

The Idaho Power Company on the 4/0-A.C.S.R. conductor of the 132-kv. Caldwell-Ontario Line.

The New England Power Company has observed that under certain conditions a charged conductor tends to vibrate, presumably from the effect of corona. While allied to the general problem of conductor vibration its occurrence is probably rare. The Pacific Gas and Electric Company has made field observations of conductor vibration, and also laboratory experiments on vibration dampers.

Space limitations prevent inclusion of more than reference to the experimental work of these and other companies. It is hoped that discussions will be presented by engineers of these companies.

Arrangement of Test Spans

At Royse City two test lines are available at an angle of 74 deg. thus insuring one line favorably exposed for vibration regardless of wind direction. The spans are 650 ft. and 1,225 ft. on the steel towers and 416 ft. and 1,226 ft. on the H-frames. Tension is adjustable at the anchorages. Observation platforms extend 12 ft. out under the conductors, Fig. 12. The ground wire on the steel towers is 3/8-inch diameter 7-strand steel, and the conductors of the 132-kv. circuit on the towers are 4/0 A.C.S.R. equipped with armor rods.

Other sizes and special types of conductors have been installed and observed for short periods.

Equipment

A satisfactory instrument for obtaining 24-hour vibration records was made by using an 8-inch diameter wax-coated, clock-driven chart on which the vertical motion of the conductor was recorded by a stylus attached to a pivoted arm. (See Fig. 13.) For small conductors the inertia and friction of the pivoted arm damped the vibration considerably and a very light stylus attached directly to the cable was substituted. This latter arrangement is satisfactory only if longitudinal motion of the conductor is restrained.

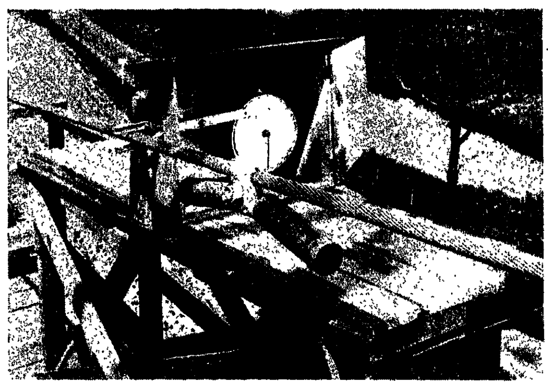

FIG. 13—VIBRATION RECORDER

A continuous record of wind direction and velocity is obtained by an anemometer which records electrically the passage of each mile of wind on a strip chart, and a weather vane with a cam-actuated pen which records direction simultaneously on the same chart. The ve-

locity for short periods is determined with a stop-watch and buzzer which indicates one-sixtieth of a mile. Fig. 14 shows two typical vibration records and a corresponding wind record.

The frequency recorder consists of a uniform speed,

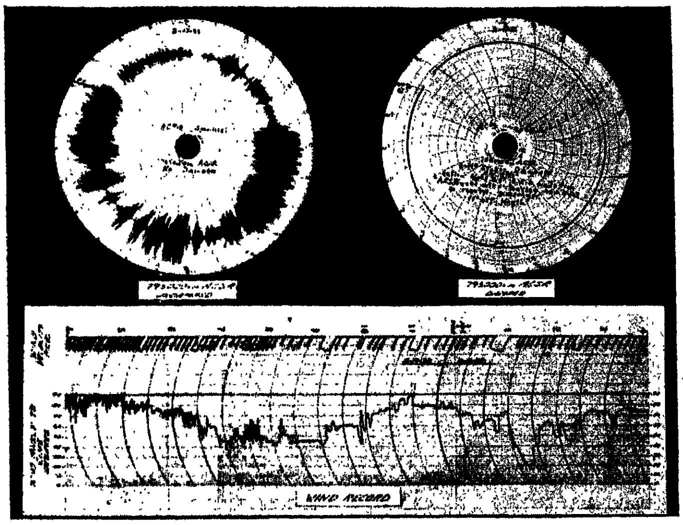

FIG. 14—TYPICAL VIBRATION AND WIND RECORDS

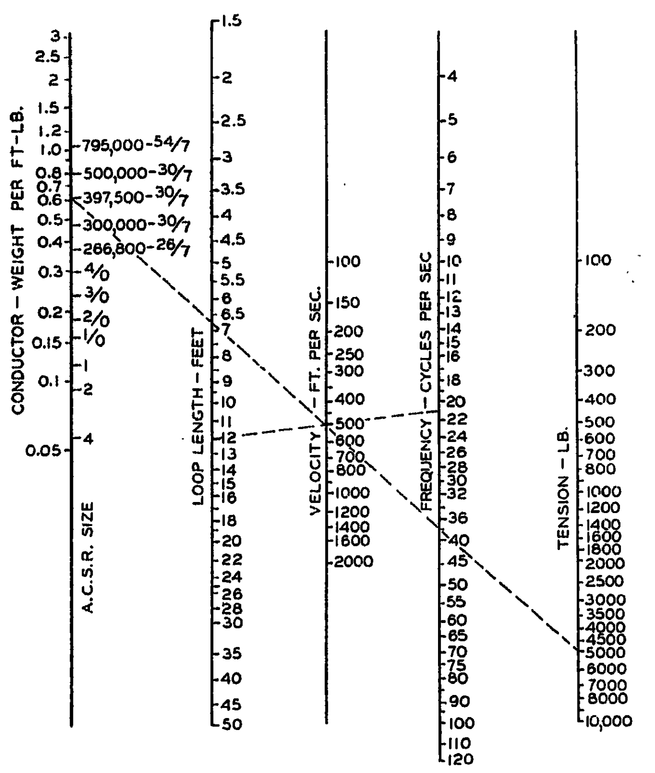

FIG. 15—RELATION BETWEEN WEIGHT, TENSION, LOOP LENGTH, AND FREQUENCY OF A VIBRATING CABLE

motor-driven strip chart on which a trace of the vibration is recorded by a pencil connected to the line by a cord and spring.

A thermograph records temperature and provision is made for observing sag and tension in the conductors.

THEORETICAL CHARACTERISTICS OF VIBRATION

Fig. 15 gives a quick solution of equation (1) showing the theoretical relations between frequency, loop length, tension, and weight of a vibrating cable for common conductor sizes and tensions.

The following formula expressing theoretical frequency of vibration was developed experimentally by Relf and Ower:

$$f = k\frac{V}{D} \tag{14}$$

where

V = velocity of wind in mi. per hr.,

D = outside diameter of the cable in inches,

and

k = a function of $\left(\frac{VD}{e}\right)$ where e depends upon the medium, e being 0.000159 for air. For ordinary sizes of conductor k is a constant having a value of 3.26.

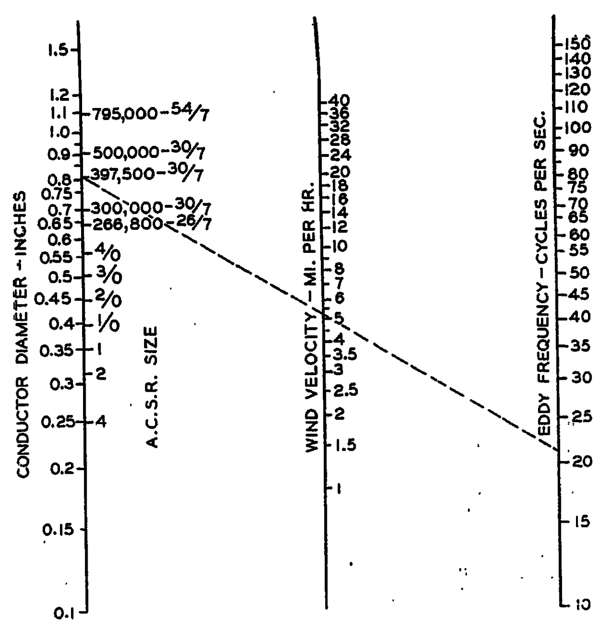

FIG. 16—WIND EDDY FREQUENCY FOR CIRCULAR CABLES (RELF AND OWER FORMULA)

A nomographic solution of this formula is given by Fig. 16.

This formula applies to a uniform wind velocity normal to the axis of the wire. Such ideal wind conditions rarely if ever exist over a transmission span. A wide variation in both velocity and direction even in short spans is shown by Professor Sherlock[12,15] at the University of Michigan. Velocity varies with elevation, and in a long span the height of conductor is not constant. Direction shifts rapidly as indicated by any weather vane. The normal component of velocity should probably be used in computing frequency when direction of the wind is oblique. This assumption seems

to be in error for very acute angles. A cable has considerable inertia and once vibrating in any particular mode will not quickly change frequency to suit slight changes in wind direction or velocity. For these reasons observed frequency sometimes differs greatly from theoretical, but with steady wind and obliquity not under 45 deg. the agreement is usually good.

Field Records of Vibration

Numerous records of frequency and amplitude for varying sizes of conductor have been obtained. Fig. 17 shows characteristic vibration records for each of four sizes of A.C.S.R. with pertinent data. The correspondence between observed and calculated frequency is fairly close. These records all show recurring beats, possibly caused by variations of wind velocity. With span length and frequency known, the time between recurrence of any particular beat determines velocity of wave propagation, tension, and theoretical loop length.

Observation proves the statement that cables of any material will vibrate when conditions are favorable. One of the earliest recorded instances of damage from vibration occurred over 20 years ago on the Carquinez Straights Crossing of the Pacific Gas and Electric Company. A few years after installation breakage of strands was discovered in the heavy plough steel conductors. It is interesting to note that the use of parallel reinforcing or stiffening cables extending some distance out from the support, which was developed here, has been repeated on many long river crossing spans.

Fig. 18 shows records of frequency and amplitude of vibration with pertinent data for conductors of materials other than A.C.S.R.

Influence of Tension

Frequency is a function of wind velocity and diameter of conductor and is independent of tension. From equation (1) it is seen that for a given frequency the loop length varies directly as the square root of the tension. Therefore, an increase in tension increases loop length and theoretically should render it more difficult for the conductor to fall into resonance with the wind eddy frequency.

Field records to determine the effect of tension were obtained at Royse City. Two No. 2 A.C.S.R. conductors were erected on a 416-ft. span with tensions of 500 and 750 lb., respectively. Simultaneous 24-hour records were taken for several weeks. Fig. 19 is a typical record indicating that both conductors vibrated for about the same period of time and that the amplitude increased slightly with the tension.

Another tension test was made on a 1,160-ft. span of 795,000 cir. mil A.C.S.R. in New Jersey. The tension was 5,400 lb. in one of the parallel conductors and 9,000 lb. in the other, a difference of over 50 per cent. Comparative records were obtained for several weeks. Vibration occurred on a few occasions only and for short periods only. Fig. 20 is typical. The recorders were set the same distance out from the supports, so the amplitudes are not directly comparable on account of difference in loop lengths.

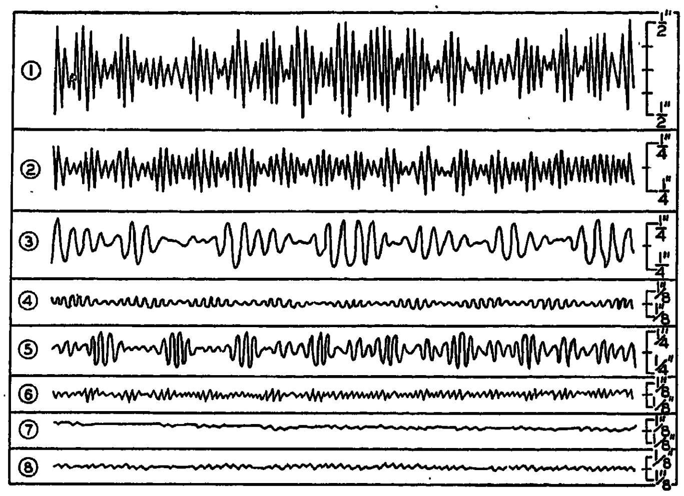

Fig. 17—Vibration Records for A.C.S.R., Royse City Experiment Station

Record No.	Conductor: Size and material	Conductor: Diameter inches	Conductor: Span feet	Conductor: Tension pounds	Wind: Velocity m.p.h.	Wind: Angle degrees	Observed vibration: Loop lth feet	Observed vibration: Amplitude 1/32 in.	Observed vibration: Frequency cy. per sec.	Calculated frequency cy. per sec.
1	795,000	1.093	1,125	8,216	8	37	24	34	12	11
2	795,000	1.093	1,125	8,216	18	68	$7^1/_2$	18	43	35
3	397,500	0.806	650	3,822	$5^1/_3$	90	15	22	21	16
4	397,500	0.806	650	3,822	$8^3/_4$	90	7	5	34	33
5	4/0	0.563	1,226	2,869	$5^1/_2$	70	$7^1/_2$	14	32	37
6	4/0	0.563	1,226	2,869	10	70	6	4	51	47
7	No. 2	0.316	650	676	5	60	$3^5/_6$	2	60	61
8	No. 2	0.316	650	676	8	60	$2^2/_3$	2	75	85

From these tests it appears that vibration will occur at any practical tension when wind conditions are favorable. A reduction of tension decreases the direct stress in the conductor but does not decrease the tendency to vibrate.

Influence of Shape

It is obvious that shape of conductor should influence vibration and field tests prove this. At Royse City the relatively smooth No. 2 and 397,500 cir. mil A.C.S.R. are observed to vibrate more frequently than the 4/0 which has a comparatively rough exterior due to larger strands.

A special test to show influence of shape was made with three No. 2 all aluminum conductors. One was single wire, one of 3 strands, and one of 7 strands. Twenty-four hour vibration charts were obtained over a period of several weeks and for several tensions. The recorders were set the same distance from the supports, and the tensions being the same, the amplitudes are comparable. Fig. 21 shows typical charts indicating that the three-strand cable vibrated least frequently and with the smallest amplitude, the seven-strand was second, and the solid wire vibrated the most. In no case was vibration prevented.

Another test was conducted on a special eccentric A.C.S.R. (418,000 cir. mils of aluminum). The outer layer of strands, being graduated in size, formed an enlargement which wound helically around the conductor axis. This cable was installed on a span of 1,125 ft. parallel to a standard 397,500 cir. mil A.C.S.R. of approximately the same diameter and proportion of steel. Fig. 22 shows a comparative record.

These experiments show that amplitude can be reduced by variation in shape but it is doubtful if a practical vibrationless conductor can be thus obtained.

Energy Transmitted to Supports

Severe conductor vibration sometimes causes supporting structural members to vibrate noticeably. Fatigue failures at bolt holes in small alloy steel cross-arm members have been reported. To measure the variation in vertical load transmitted to the structure a small rod of high elastic limit steel was inserted between the suspension clamp and the insulator string on a 1,125-foot span of 795,000 cir. mil A.C.S.R. An accurate load-deformation curve for this rod had previously been determined with a Huggenberger tensometer. A number of readings was made under varying conditions

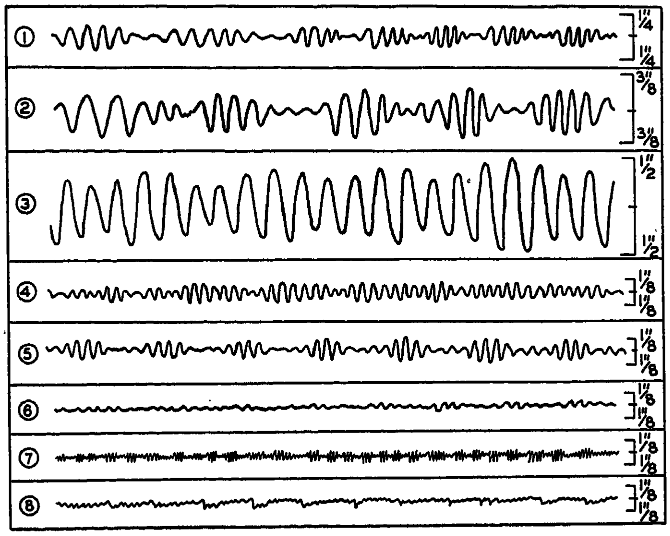

Fig. 18—Vibration Records for Cables of Various Materials

Record No.	Conductor: Size and material	Conductor: Diameter inches	Conductor: Span feet	Conductor: Tension pounds	Wind: Velocity m.p.h.	Wind: Angle degrees	Observed vibration: Loop lth. feet	Observed vibration: Amplitude 1/32 in.	Observed vibration: Frequency cy. per sec.	Calculated frequency cy. per sec.
1	650,000 cm. Cu. Calson Bze. Core	1.13	835	9,500	4.5	90	11.5	12	16	14
2	650,000 cm. Cu. Calson Bze. Core	1.13	835	9,500	2	85	17.7	19	10	9
3	400,000 cm. 19 str. cu.	0.728	1,200	5,100	4	70		32	21	18
4	250,000 cm. 19 str. cu.	0.575	1,125	5,550	5.75	66	8.	9	29	30
5	250,000 cm. 19 str. cu.	0.575	1,125	5,550	6.	66	8.	9	25	31
6	4/0 Copper	0.528	750	3,200	6.8	80	6.9	6	25	29
7	3/8 Steel	0.375	650	3,800	8.75	90	3.75	4	88	89
8	3/8 Steel	0.375	650	3,800	10	75	3.	3	99	102

of vibration. The variation in vertical load was of the order of 100 to 150 lb.

Moving Pictures of Vibrating Cable

Sixteen exposures per second with an ordinary moving picture camera is too slow to show vibration at a frequency of 25 cycles or more. A high-speed camera

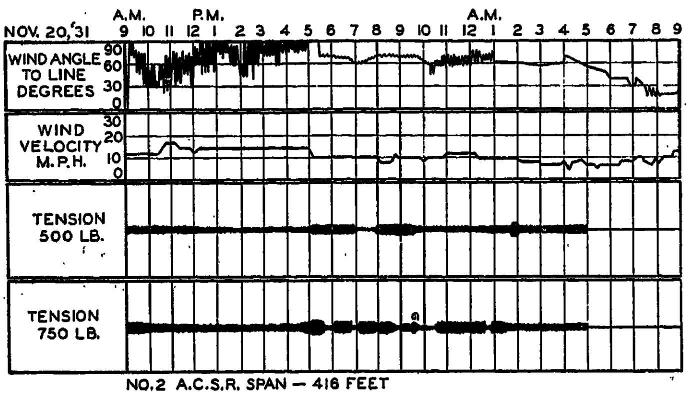

Fig. 19—Vibration Records Showing Effect of Tension, Royse City Experiment Station

taking 128 exposures per second "slows down" the vibration so that the motion of the cable can be readily followed on the screen. One reel was taken of a 795,000 cir. mil A.C.S.R. in the afternoon when the wind velocity was high and the cable vibrating with short loop-length, high frequency, and small amplitude. A second reel was taken about midnight under flood lights when wind velocity was low with correspondingly lower frequency, longer loop length, and greater amplitude.

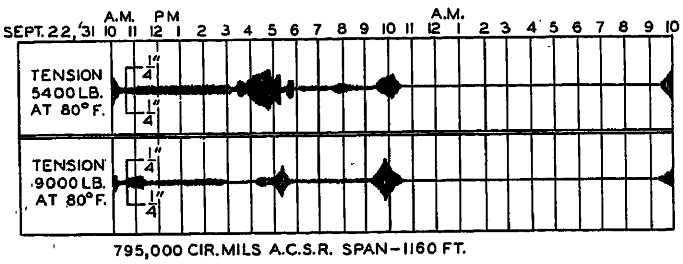

Fig. 20—Vibration Records Showing Effect of Tension, Roseland-Bushkill Line

Rocking of the suspension clamp is clearly shown and beat pulsations are evident.

Effect of Dampers

The problem of damping a vibrating conductor differs from many vibration problems in that the damper must be effective over a wide range of frequencies. This precludes the use of a tuned dynamic vibration absorber for which the theory was presented by J. Ormondroyd and J. P. DenHartog.[7] Such an absorber theoretically consumes no energy and it seems that it can not damp vibration where there is a continuing input of energy as on a transmission line. The dynamic absorber with damping is effective over a broad band of frequencies and also consumes energy. The theoretical formulas in the Ormondroyd-DenHartog paper for this type of damper are applicable to a vibrating cable in principle only and require extensive modification and laboratory determination of certain constants.

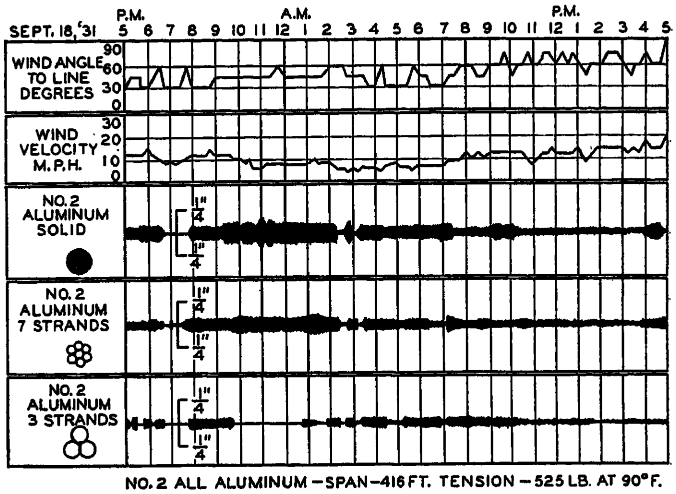

Fig. 21—Vibration Records Showing Effect of Stranding, Royse City Experiment Station

It is of interest to note that a simple weight of suitable size at the center of one loop of a vibrating cable

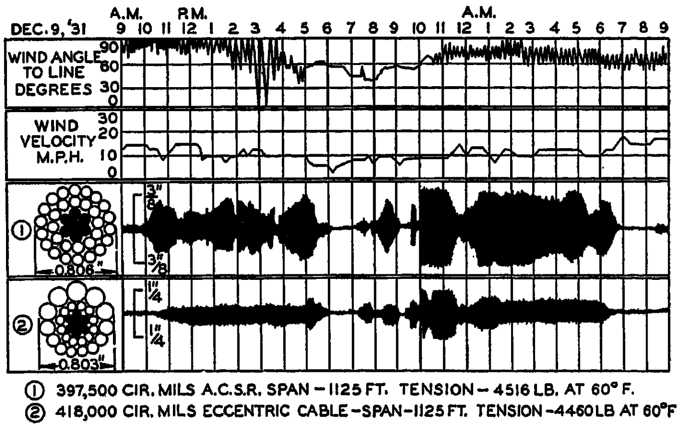

Fig. 22—Vibration Records Showing Effect of Eccentric Shape, Royse City Experiment Station

is somewhat effective as a damper. The added weight alters the natural period of that one loop and, with the forced vibration which then ensues in that particular loop, the vibration is damped by consumption of energy in the conductor itself in that loop. The practical difficulty is that a node is soon established at the weight and vibration is renewed.

The energy which must be consumed to damp vibration is undoubtedly very small in amount. This is

evident from the theoretical formula developed by Bate[10] for the input of energy to a cable from the wind eddies. His formula involves several assumptions which have not been proved but the method of derivation is logical

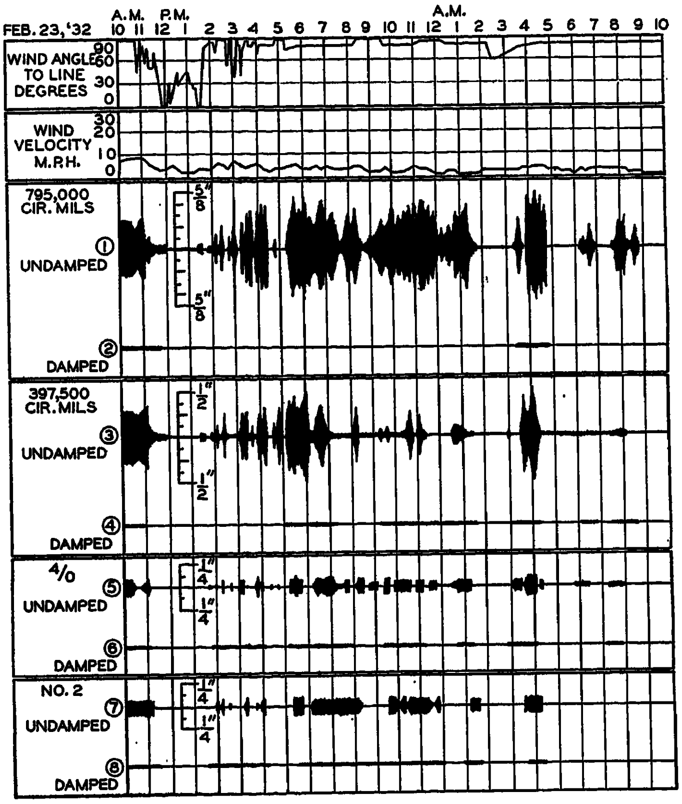

Fig. 23—Vibration Records Showing Effect of Dampers on A.C.S.R., Royse City Experiment Station

	A.C.S.R. Conductors				Recorder
Record No.	Size in cm. or B & S gage	Diam. in inches	Span in feet	Tension in lb. @ 60° F.	Distance from support
1	795,000	1.093	1,125	6,755	5 ft. 2 in.
2	795,000	1.093	1,125	6,810	5 ft. 0 in.
3	397,500	0.806	1,125	4,200	4 ft. 5 in.
4	397,500	0.806	1,125	4,085	2 ft. 9 in.
5	4/0	0.563	416	2,025	2 ft. 9 in.
6	4/0	0.563	416	2,000	4 ft. 0 in.
7	No. 2	0.316	416	740	3 ft. 1 in.
8	No. 2	0.316	416	720	3 ft. 1 in.

and dimensionally it is probably correct. The formula gives the energy input per loop per cycle, G in ft.-lb., as follows:

$$G = 0.000022\, V^2 D A L' \qquad (15)$$

where, as previously,

V = velocity of wind in mi. per hr.,

D = outside diameter of the cable in inches,

A = amplitude of vibration in inches,

and

L' = loop length or distance between node points in ft.

This formula shows the input of energy proportional to the amplitude, hence if amplitude can be restrained to a small value the energy input will be small. This agrees with the observed fact that vibration builds up slowly and is easily damped at first.

One reason for the outdoor laboratory was to study the action of dampers. The usual method of observation is by comparison of 24-hour vibration records from two conductors identical in size, span length, and tension, one damped and the other undamped.

Many different dampers have been tested at Royse City, hundreds of comparative records being obtained. The most successful type is essentially a mass resiliently attached to the conductor in the loop nearest the support and so designed that energy is consumed by friction or hysteresis.

This damper was developed by Geo. H. Stockbridge of the Southern California Edison Company. The usual form consists of two weights connected by a short piece of stranded steel cable, this assembly being attached to the conductor a short distance out from the insulator. This damper is simple and practical to construct and easy to install, even on hot lines. The weight, size and length of stranded cable, and location in the span vary for different diameters of conductor. For spans of moderate length, say under 1,000 ft. one damper at each end of the span is required. Fig. 23 shows comparative 24-hour records with pertinent data for a damped and an undamped span of four sizes of A.C.S.R. at Royse City, including wind direction and velocity recorded at one end of the span. It is evident that the dampers suppressed practically all visible vibration.

It is obvious that energy input from the wind is directly proportional to length of the span. In long spans better damping is obtained with two dampers at each end. Three or more may be required on extremely long spans.

A damper cannot act effectively until the conductor vibration acquires a certain amplitude. This is manifested by a slight quiver which can be felt although barely visible. The 24-hour charts do not show this very clearly. Recently a series of records from a free and a damped span of 4/0 A.C.S.R. was obtained by engineers of the Idaho Power Company using a carbon pile oscillograph. Fig. 24 shows two of their oscillograph records. The ripple in the damped cable is scarcely visible even at the enlarged scale.

Many tests of Stockbridge dampers have been made to determine the best dimensions and location. The dampers are not critical either as to size or spacing. A variation of 25 per cent in any factor will not seriously affect performance. Fig. 25 shows the style of Stockbridge damper used. To avoid corona discharge this design embodies cylindrical weights which shield the damper cable and a clamp having no sharp corners.

Armor Rods

Armor rods are primarily reinforcement but they are also effective as dampers. Numerous comparative records have indicated that they reduce amplitude from

10 to 20 per cent. They reduce stresses by distributing the bending from vibration, reinforce the cable at the point where the stresses are greatest, and furnish valuable protection against flashover burns.

4. Certain types of cable accessories have marked effects on the life of vibrating conductors.

5. Theoretical formulas[2] expressing relationship between frequency, loop length, tension and weight of a vibrating conductor are in good agreement with field observations.

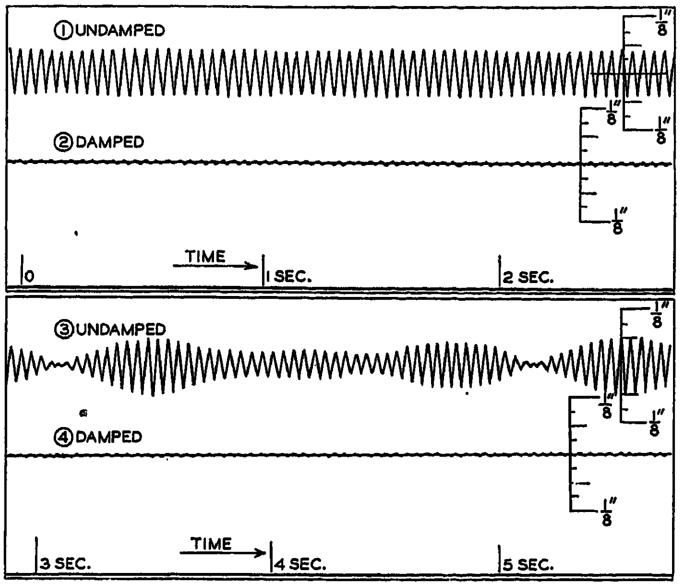

FIG. 24—VIBRATION RECORDS SHOWING EFFECT OF DAMPERS ON 4/0 A.C.S.R., CALDWELL-ONTARIO 132-KV. LINE

	Conductor				Wind		Observed vibration			
Record No.	Size in cm. or B & S gage	Diameter inches	Span feet	Tension pounds	Velocity m.p.h.	Angle degrees	Loop lth. feet	Amplitude 1/32 in.	Frequency cy. per sec.	Calculated frequency cy. per sec.
1	4/0 A.C.S.R	0.563	550	2,630	3	75	11.95	6	23	22
2	4/0 A.C.S.R	0.563	550	2,630	3	75				
3	4/0 A.C.S.R	0.563	550	2,650	4	75	11.7	8	23	22
4	4/0 A.C.S.R	0.563	550	2,650	4	75				

Conclusions

1. Satisfactory methods have been developed for measuring actual stresses in vibrating conductors under conditions closely simulating field conditions.

2. A mathematical analysis of the stresses in a stranded conductor under vibration is given which checks closely with measured values.

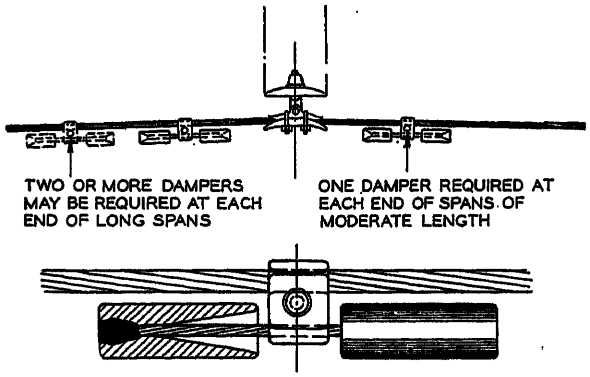

FIG. 25—STOCKBRIDGE DAMPER ASSEMBLY

3. Tests indicate that safe limits for stress ranges of conductor materials can be satisfactorily determined.

6. The Relf and Ower formula[2] for the frequency of a vibrating cable is substantially correct.

7. Any suspended cable will vibrate when conditions are favorable.

8. Any feasible reduction in tension will not prevent vibration.

9. Modifications in shape of cross section and stranding have some beneficial effect in reducing amplitude but the results do not support the idea that a vibrationless cable can be evolved.

10. The variation in vertical load transmitted to the insulator is not large.

11. Slow-motion moving pictures of vibrating cable enable the motion to be followed by eye but have been of little assistance.

12. A properly designed damper will prevent the building up of any appreciable amplitude and since the input of energy from the wind varies directly as the amplitude an effective damper is required to absorb very little energy.

13. The Stockbridge damper gives best results, is simple in design and construction, has no moving parts and is easy to install.

14. Armor rods are primarily reinforcement although they reduce the amplitude of vibration from 10 to 20 per cent.

16. Adequate practical protection against damage from vibration of conductors is afforded by proper use of armor rods or dampers.

Acknowledgments

Acknowledgment is due the associates of the authors on the technical staff of the Aluminum Company of America for the assistance which they have contributed. The writers are particularly indebted to George W. Stickley in charge of the test work at Massena, H. L. Anderson in charge of observation work at Royse City Field Experiment Station, and R. G. Sturm, who has contributed the mathematical analysis of stresses in vibrating cables and dampers.

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Discussion

For discussion of this paper see page 1076.

Transmission Line Vibration Due to Sleet

BY J. P. DEN HARTOG*

Non-member

Synopsis.—With sleet, a temperature just below the freezing point, and with a heavy wind blowing transversely across a transmission line, vibrations of amplitudes up to 20 feet have been observed An explanation of this phenomenon is given.

INTRODUCTION

THE subject of vibration in transmission lines due to the action of a transverse wind has been frequently discussed in the technical literature of the last few years. The phenomena encountered mostly are those occurring at moderate wind velocities (about 5 miles per hr.), characterized by rather high frequencies (5 to 15 cycles per second) and small amplitudes, up to a few cable diameters. This type of vibration is caused by the Kármán vortexes forming behind the wire and is well understood.

Another type of disturbance has been observed, which seems to occur with sharp winds of above 20 miles per hour, with great amplitudes (20 feet), slow frequencies (one cycle per second or slower), and mostly associated with sleet formation on the conductors. This phenomenon has been described in detail in a paper by Davison,† who rightly believed it to be caused by the change in shape of the conductor due to the ice coating and by the consequent change in aerodynamic lift. Davison measured the lift of some specimens in the wind tunnel and found that the lift under certain conditions can even exceed the weight of the cable. However the mere fact that the wind causes a lift on the unsymmetrical conductor does not yet cause it to vibrate, so that Davison's discussion of the phenomenon is incomplete.

It is the object of this paper to give an explanation of the effect, and to show how the stability of a transmission line in this respect can be calculated from the results of an aerodynamic test, whereby both the lift and the drag are determined for various angles of attack.

QUALITATIVE EXPLANATION

Consider an element of the cable of unit length subjected to a lateral wind of constant velocity V and vibrating up and down according to $x = a \sin \omega t$. On account of its vibrating motion the cable experiences a vertical wind component in addition to V.

For instance at the instant that the cable is moving upward with the velocity v the "relative wind" striking it appears to come from above under an angle

$$\Delta \alpha = \tan^{-1} \frac{v}{V},$$

Fig. 1. Since during the vibration the velocity v varies all the time it is seen that the cable is subjected to a wind of which the direction also varies with the time. For a cable of circular cross-section the force exerted by the wind on it will be always exactly in the direction of the wind, or, in aerodynamical parlance, there is only drag, and no lift. In case the cross-section becomes non-circular due to sleet, this ceases to be true and lift as well as drag appears.

Plotting the drag (= wind force in the direction of the wind) as well as the lift (= wind force perpendicular to wind direction) against the angle of attack for an elliptic cross-section Fig. 2 is obtained. The drag is a minimum for $\alpha = 0$, and a maximum for $\alpha = 90$ deg. Due to symmetry the lift must be zero at $\alpha = 0$ and $\alpha = 90$ deg. and it reaches a maximum in between. It is an experimental fact that this maximum is closer to 0 deg. than to 90 deg. For α between 90 and 180 deg. there is negative lift or downpush.

Now consider a cable element having an elliptical section in the position of $\alpha = 0$ deg. in Fig. 2 and let it

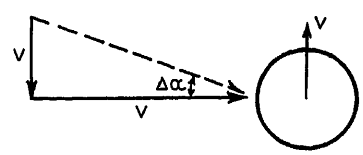

FIG. 1

vibrate vertically. While it is moving upwards the relative wind strikes it obliquely from above (Fig. 1) and the angle $\Delta\alpha$ is negative (Fig. 2). In other words, while the cable is moving upwards it experiences an aerodynamic downpush. In the same manner it can be seen that during downward motion there is lift, so that always the force is directed against the motion. Whenever such a vibration starts the wind will damp it out.

The conditions are quite different however when the cable has the position $\alpha = 90$ deg. in Fig. 2. Incidentally, such a cable has some resemblance to a line with icicles hanging down vertically from it. While the cable is moving upwards the angle of attack is 85 deg. say instead of 90 deg. and there is *lift;* similarly, during downward motion the angle α is 95 deg. and there is downpush. The forces are in the direction of the velocity of vibration and therefore put energy into the motion. The cable is unstable; any vibration, however small, will be increased in amplitude by the wind.

It is seen that this instability is due to the *negative slope of the lift curve;* a cable in a position $\alpha = 60$ deg. in

*Research Laboratories, Westinghouse Elec. & Mfg.Co., East Pittsburgh, Pa.

†*Dancing Conductors*, C. E. Davison, TRANS. A.I.E.E., Vol. 49, 1930, p. 1444.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

Fig. 2 would be unstable also. There would be only a constant lift superposed on the variable lift due to vibration. This constant lift only would relieve the towers of some of the load, but would have no other effects.

So far we have not considered the drag force. Fig. 3 represents the forces acting on a cable element in the

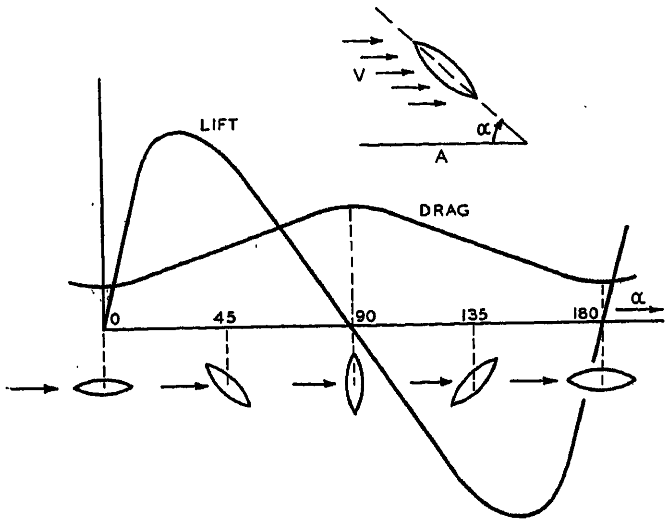

FIG. 2

position $\alpha = 90$ deg. of Fig. 2 while in its upward stroke during the vibration. It is seen that not the entire lift force is pushing the cable up, but only its vertical component, and it is also seen that the drag force has a *downward* component. Therefore *instability occurs when the effect of the negative slope of the lift curve is greater than the damping action due to the drag.*

QUANTITATIVE THEORY FOR SMALL VIBRATIONS

Assume that for the cross-section under investigation

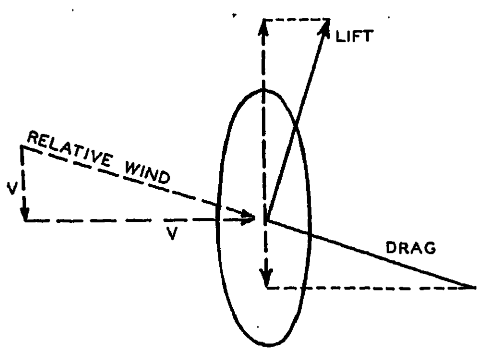

FIG. 3

a lift and drag diagram like Fig. 2 has been determined experimentally by a wind tunnel test. The diagram holds for a particular wind velocity V_0. The lift and drag forces for other wind velocities can be calculated by observing that they are proportional to the square of V.* Therefore the lift is:

$$L = \frac{V^2}{V_0^2} \cdot L_0 \tag{1}$$

where L_0 is the ordinate of Fig. 2. A corresponding relation is true for the drag.

Let the cable element execute small vibrations $a \sin \omega t$. The vertical velocity v then is $a\ \omega \cos \omega t$ and the variation in the angle of attack (Fig. 1) is:

$$\Delta\alpha = \frac{a\,\omega}{V} \cos \omega t$$

For small $\Delta\alpha$ the lift curve is a straight line and the drag can be considered constant. Then the lift is:

$$\frac{dL}{d\alpha} \cdot \Delta\alpha$$

where $dL/d\alpha$ is the negative slope of the lift curve. Let D be the drag at the point considered; then according to Fig. 3 the vertical component of the drag is $D \cdot \Delta\alpha$. Consequently the driving force is:

$$\left(\frac{dL}{d\alpha} - D\right)\Delta\alpha = \frac{a\ \omega}{V}\left(\frac{dL}{d\alpha} - D\right)\cos \omega t$$

In this expression L and D are still functions of the wind velocity; with (1) the driving force becomes:

$$\frac{a\omega V}{V_0^2}\left(\frac{dL_0}{d\alpha} - D_0\right)\cos \omega t \tag{2}$$

This driving force is of the nature of a negative "viscous" damping. Sustained vibrations occur when

$$\frac{dL_0}{d\alpha} > D_0 \tag{3}$$

The expression $dL_0/d\alpha$ is the vertical distance between the two points of the tangent to the L_0-curve whose horizontal distance apart is 1 radian or 57 degrees. When this distance in Fig. 2 is greater than the ordinate of D_0 at that point the cable is dynamically unstable. The formula also shows that the effect, whether it be input or damping, is proportional to the velocity of the wind.

In order to get a quantitative idea about the order of magnitude of the effect it is necessary to possess experimental lift-drag-α diagrams, like Fig. 2, for the various ice-coated shapes that are likely to occur. Such diagrams do not exist at present. Davison only gives the lift curves in his paper. There are lift and drag curves for a number of airfoil sections,† which, when held vertically, resemble to a certain extent a cable with icicles. These airfoil curves show several ranges of α where the $dL/d\alpha$ term is considerably greater than the D-term.

Taking Fig. 5 of Davison's paper, it can be calculated that the part of the driving force due to the $dL/d\alpha$ term

*It is understood that this is only approximately so; for airfoil sections in aeronautics the approximation is very good, but for irregular sections as discussed here the error may be considerable.

†"Lift and Drag of Aerofoils Measured Over 360 Deg. Range of Incidence," Lock and Townsend. Reports and Memoranda of the Aeron. Res. Committee, No. 958, London 1914. Also Prandtl and Betz, "Ergebnisse der Aerodyn. Versuchsanstalt zu Göttingen," Vol. 3, p. 78.

is more than 20 per cent of the maximum inertia force of the cable during vibration. Though from this the damping force due to the D-term has to be subtracted, it is clear that the forces are of the right order of magnitude to explain the field observations.

Calculation of the Amplitude

The theory given so far is limited to small amplitudes, because the slope of the lift curve as well as the amount of drag were assumed to be constant. For large vibrations this ceases to be true, and then it becomes necessary to divide the path of motion of the conductor into a number of sections and to determine for each of these sections the driving force in much the same manner as equation (2). Each of these forces has to be multiplied by its respective path in order to obtain the work done. For small vibrations the work during one cycle will be positive, so that the motion will increase. For larger amplitudes, however, certain parts of the motion will have a negative driving force or damping. This occurs

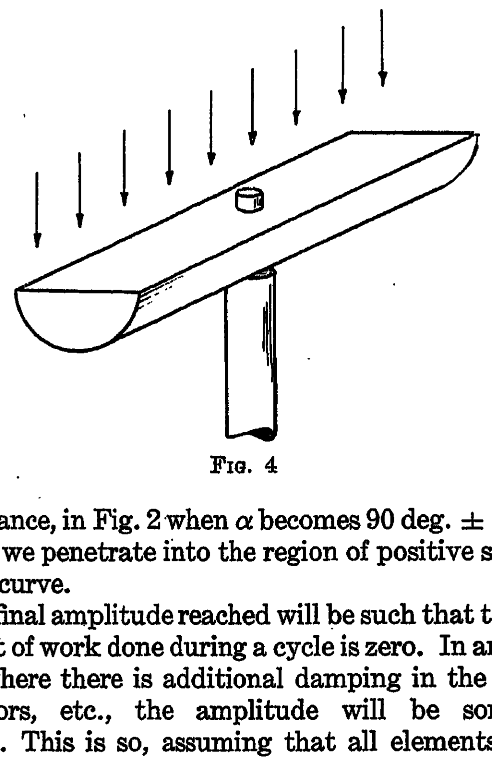

Fig. 4

for instance, in Fig. 2 when α becomes 90 deg. $\pm$ 75 deg., so that we penetrate into the region of positive slopes of the lift curve.

The final amplitude reached will be such that the total amount of work done during a cycle is zero. In an actual case, where there is additional damping in the towers, insulators, etc., the amplitude will be somewhat smaller. This is so, assuming that all elements of the line have the same amplitude. In reality this is obviously not the case, and then the total work input by the wind has to be calculated for all elements of a span. Assuming that the span vibrates somewhat like a string, *i.e.*, in a sinusoidal form, this calculation is a straightforward process involving no particular difficulties.

Related Phenomena

The effect can be observed by means of a very simple experiment. Take a stick of rectangular cross-section, a common yardstick for instance; hold one end in the hand and dip the other end vertically into the bath tub. When the stick is pulled through with the narrow side in front, it is in the stable position, $\alpha = 0$ deg. of Fig. 2, and nothing will happen. When it is pulled with the broad side in front, however, $\alpha = 90$ deg. and the condition is unstable. It will be found difficult to pull the stick through along a straight path; it will rather vibrate back and forth just like the transmission line.

A toy, described and explained by Lanchester* and named by him the "aerial tourbillion," operates on the same principle. (Fig. 4.) It consists of a stick of semi-circular cross-section which can turn about an axis. When it is held in the face of a strong wind and started rotating it will keep on doing so. The direction of rotation is immaterial; it will persist in whatever direction it is started. It is evident that the semi-circular section can be replaced by any cross-section which would also cause a transmission line to vibrate, and consequently would satisfy equation (3). If the bearing could be made without any friction, this would probably be the easiest experiment by which various cross-sections could be tested on their stability.

Conclusions

1. The slow vibrations of ice-coated transmission lines in a heavy wind can be explained as due to a certain aerodynamic instability.
2. The phenomenon is entirely different from and has no connection with the rapid vibrations observed in fair weather at moderate wind velocities.
3. It is shown that instability occurs when the negative slope of the "lift curve" is greater than the amplitude of the "drag curve."
4. It follows from the theory that a change in the span length or in the tension of the cable does not affect the phenomenon.
5. The behavior of a toy, called the "aerial tourbillion" is shown to afford a simple test by which the stability of various ice-coated sections can be determined.

Discussion

VIBRATION AND FATIGUE IN ELECTRICAL CONDUCTORS
(Davison, Ingles and Martinoff)

STRESS-STRAIN STUDIES OF TRANSMISSION LINE CONDUCTORS
(Stickley)

VIBRATION OF OVERHEAD TRANSMISSION LINES
(Monroe and Templin)

TRANSMISSION LINE VIBRATION DUE TO SLEET
(Den Hartog)

John A. Koontz: A careful study of the vibration problem was first undertaken after trouble had developed in some of the early Stockbridge type damper designs. This trouble was due to fatigue of the supporting messenger strand. Life tests were made on the early assemblies and it was soon found that it was necessary to substitute high strength steel strand in place of the ordinary guy strand or Siemens-Martin grade. This substitution changed the characteristics of the damper slightly, but later tests proved that they were still effective. The life tests were made on the damper assemblies using a vibration machine similar to that

*F. W. Lanchester, *Aerodynamics*, London, 1907 and 1923, p. 45.

shown in Fig. 10 of the paper by Messrs. Monroe and Templin. The revised damper design, using the high strength steel, was given a life test of over one hundred-million cycles without failure. The failures in the supporting strand occurred not at the center clamp or point of maximum stress but where the cable enters the weight, or at a point where the strand is subjected to a reversal of stress.

Messrs. Monroe and Templin seem to favor two dampers per wire per span wherever possible. I prefer using four dampers for any line of 1.00-in. diameter or larger. The four dampers should have their spacing staggered. This is done so that not more than one damper would be located at a node point for any frequencies most generally experienced. This method as a rule permits three

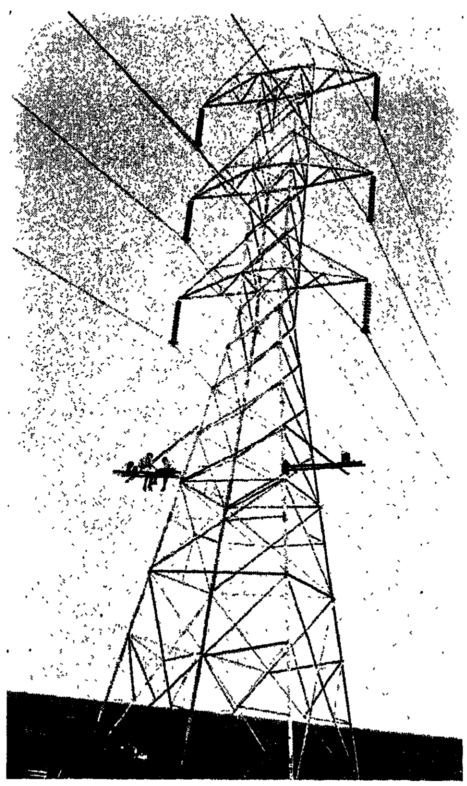

Fig. 1—Mounting of Recorders on a Tower Line Having One Aluminum and One Copper Circuit

dampers to be so located that they may be fairly effective as dampers. A damper has its greatest efficiency when located at the center of a loop, and the Stockbridge damper is most efficient when the natural period of the damper is approximately that of the vibrating cable. In order to make a more careful study of damper spacing, a test span was erected and this span was vibrated mechanically from 4 to 22 cycles per second. After studying the damper spacing on this short span the test equipment was transferred to the field and the actual spans on the towers were vibrated and the laboratory results checked. These tests all seem to indicate that this staggered spacing and the use of four dampers were much more satisfactory than when only two dampers were used. With modern design dampers of the Stockbridge type properly designed and located, I believe it is possible to take care of vibration so that no damage will be done to the conductor.

In connection with our study of this problem, the majority of the testing was done on an aluminum line which is one circuit on a double circuit 220-kv. tower line. The aluminum circuits consist of three 795,000-cir-mil steel core aluminum cables having a conductivity equal to 500,000-cir-mil copper. On the opposite side of this same tower there are 3 hollow core copper cables of 1-in. diameter having a section of 509,400 cir. mils. Both sets of cables are erected to give the same ground clearance, and hence have the same sag. This line represents almost ideal conditions to check relative vibration on these two types of conductors. The cables are parallel with only 27 ft. of horizontal separation at equal height above ground and supported in the same manner so that all spans are alike. A study of the relative vibration of the two conductors was undertaken and vibration recording equipment was installed, as shown in Fig. 1. This equipment was arranged to take simultaneous records. The observations were carried on for several weeks at a time when conditions were rather favorable for vibration. Fig. 2 shows the actual field records as taken and gives a rather clear conception of the relative vibration. It will be observed that the copper and aluminum cables vibrate at approximately the same time. Loop lengths were observed to be of the same magnitude and the conductors vibrate at approximately the same frequency, but the amplitude of the vibration of the copper conductor is less. This is clearly shown in Fig. 3.

It may be of interest to operating engineers to know that these records were taken while the lines were in operation; the aluminum line operating at 165,000 volts and the copper line at 220,000 volts. These records were taken by attaching the arm of the vibration recorders to the line wires by specially treated cords. The recording instruments were placed approximately 20 ft. directly below the conductor. The records were traced on a Bristol smoked chart.

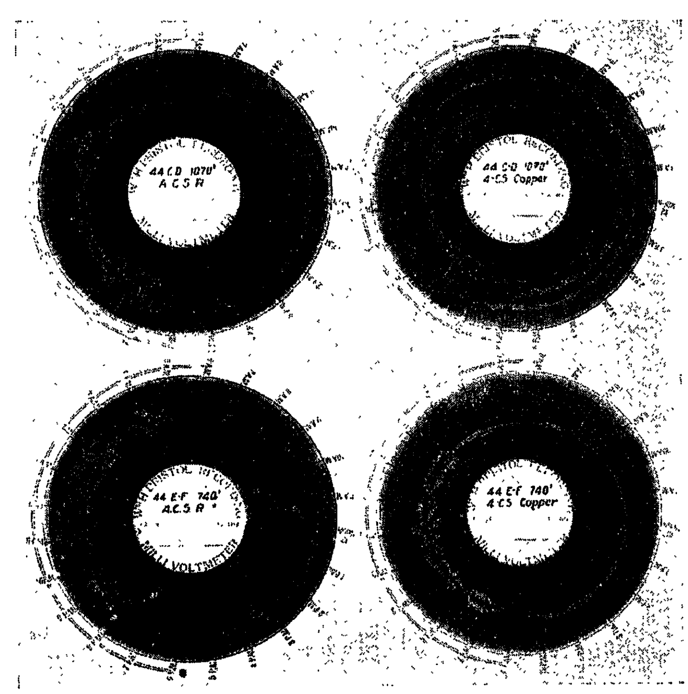

Fig. 2—Record of Vibration

There is one other point in connection with the vibration of transmission line conductors, that is, vibration in general occurs during the night hours, late in the evening, or quite early in the morning. The wires seldom vibrate during the usual working hours of the day. This point has led some engineers to believe their lines free from vibration.

F. E. Andrews and H. T. Eddy: The subject discussed in Mr. Den Hartog's paper is that which is generally known as "whipping" rather than that which is generally known as "vibration." The paper would be considerably improved by restricting the use of the term "vibration" to disturbances such as are described in the first paragraph.

The statement is made in the second paragraph that disturbances of greater amplitude (20 ft.) are mostly associated with ice. If the theory advanced by this paper is correct, and it is the same theory advanced by Mr. Davison and which is generally accepted, the disturbances cannot arise without ice. I should like to have this statement checked by Mr. Den Hartog.

The cause of the vertical lift shown in Fig. 3 of the paper is not clear. The lift is given as a function of the velocity but it is shown with a greater force than the drag. Is this vertical lift the vertical component of the wind acting upon the conductor or is it the result of eddy currents?

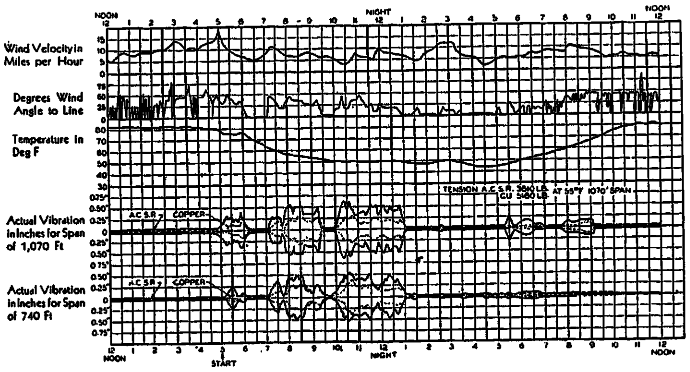

FIG. 3—SIMULTANEOUS RECORDS OF WIND VELOCITY AND DIRECTION, AIR TEMPERATURE, AND THE VIBRATIONS ARISING FROM THESE CONDITIONS IN PARALLEL COPPER AND ALUMINUM CONDUCTORS

——— A.C.S.R., 795,000 cir. mil, 1.093-in. diam.
– – – – Copper 500,000 cir. mil, 4OS hollow core, 1-in. diam.

At other places in the discussion, vibration, presumably caused by eddy currents, is assumed as the originator of action and as the cause of variation of the angle of attack. If this is accepted we would be able to prevent whipping by preventing vibration with dampening devices, but anyone who has seen the violent whipping action would be slow to accept such a solution.

The conclusion that change in span length or change in tension of the cable does not affect the phenomenon is contrary to generally established formulas for traveling waves in a conductor. It also raises doubt as to the practicability of the theory. It is well known that there may be no disturbance in spans adjacent to those in which violent whipping is in process and which are seemingly similar in all respects, except for slight difference in span length or in tension. Such considerations and the additional complications of friction, inertia of clamps and suspension insulators, stiction, etc., make it seem impractical to predict whipping by application of formulas here developed.

In the paper by Messrs. Monroe and Templin we ask the reason for the Fig. 6 in equation (1). This equation is normally written;

$$f = \frac{1}{L}\sqrt{\frac{Tg}{W}}\,.$$

In discussing the paper by Messrs. Davison, Ingles, and Martinoff: there are several 3-strand conductors now on the market, notably one of high strength material made by the Aluminum Company. Has there been any experience with the use of sleeves on this conductor and is any special sleeve necessary?

C. B. Basinger: It has been suggested that there is a cause of conductor vibration which is closely allied with the phenomenon of corona discharge, and which, though affected by it, is not wholly dependent upon wind for its action.

This discussion presents the results of experiments made by Mr. H. L. Richardson and the writer, at the Massachusetts Institute of Technology, to study the forces which act on a moving conductor which is surrounded by corona discharge. These studies show that a force exists which is a function of the voltage on the conductor and of the velocity of the conductor relative to the air. In general it is necessary for the conductor to be energized above the corona voltage and a further increase in voltage, over the range studied, increases the force. For this reason, in this discussion the force is called "corona force."

A glass frame, shown diagrammatically in Fig. 4, was constructed of pyrex tubing and supported at the top from a wood structure by means of a small precision ball bearing. A direct-current watt-hour meter was placed under the frame and mechanically connected with it by means of a fiber rod, so that it could be used to drive the rotating structure with easily measurable torques. Polished conductors were placed between the upper and lower arms of the frame and connected to the high-voltage source by means of fine wires inside the tubing. Both conductors were connected together and to one side of a high potential transformer, the other side being grounded. Thus, when the frame was rotated by the watt-hour meter, an arrangement was provided for moving the conductors through the air at various speeds while high potential was applied to them. The connecting wires being inside the tubing, the corona

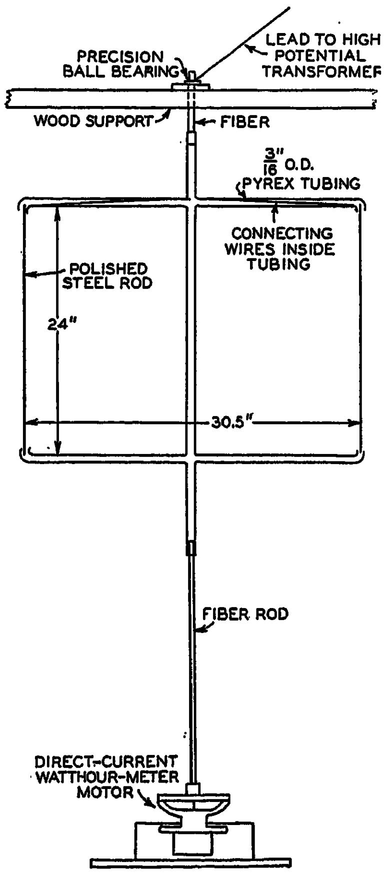

FIG. 4—DIAGRAM OF GLASS FRAME AND DRIVING MOTOR

discharge from them had no effect upon the turning of the frame, and whatever force was observed could be attributed only to the exposed conductors held between the four projecting arms of the frame.

The watt-hour meter motor was calibrated for torque by means of a spring; thereafter torques were determined from the meter field and armature currents. It was therefore possible to plot speed-torque curves for the combination of the motor and the frame, with various voltages applied to the conductors; from the speed-torque curves the force due to the voltage was readily derived.

At any given speed the friction inside the meter, as well as the outside friction on the frame, was the same with and without voltage on the conductors. Also, at any given speed the internal torque supplied by the meter was the same for these two conditions. Therefore, the difference in torque required, with and without voltage, to drive the frame at any given speed is the torque supplied by the electrical force on the conductors at that speed.

Throughout the tests three different sizes of conductor were used: 2.4 and 1.6 mm. steel rods, and 0.8 mm. copper wire. Three voltages, 76.7, 62.4 and 48.0 r.m.s. kv. were used in connection with each of the three sizes of conductor. In all cases the recorded speeds of the conductors through the air were determined by timing the revolutions of the frame after the steady state had been established. Speed-torque curves were plotted in terms of the speed of the conductors through the air in centimeters per second, and the torque required, in gram-centimeters, and in each case a curve was plotted for both directions of rotation.

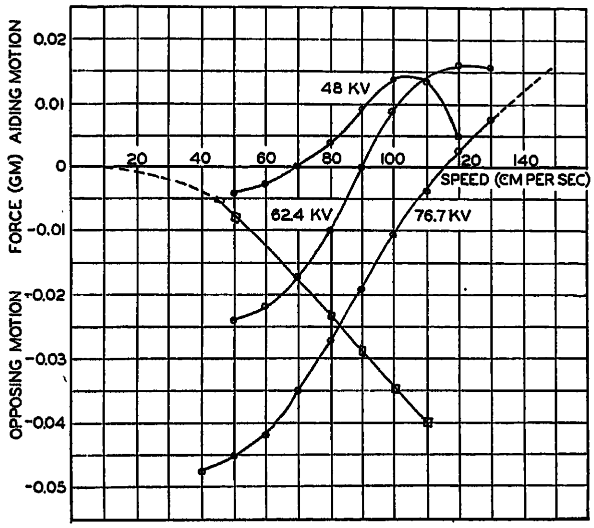

Fig. 5—Speed Force Curves for a 61-Cm. Length of 0.8 Mm. Wire

The corona force speed curves were determined from the difference between the speed-torque curve with no voltage and the average of the speed-torque curves in each direction with voltage applied. The averaging of the torques in each direction balanced out any inherent dissymmetry.

In Figs. 5, 6 and 7 are shown the curves of force on a 61-cm. length of conductor as derived from the speed-torque curves. The force is shown in grams and the speed of the conductor in centimeters per second. The force over the range of velocities studied seems to be somewhat cyclic in nature, being negative or such as to retard the motion of the wire at very low speeds, and positive or such as to accelerate the motion at somewhat higher speeds. Furthermore, in the case of the 0.8 mm. wire, the maximum magnitude of the force in the negative region is considerably greater than that in the positive region. Another interesting point is that the speed for the maximum positive force becomes less as the size of the conductor is increased. In each figure the curve of air resistance for the size of wire in question is also plotted, so that the order of magnitude of the force due to voltage, or the corona force, may be compared with it.

It is realized that the method of arriving at the corona force *versus* speed, which was followed, is an inherently inaccurate one. That is, the difference between two fairly large quantities is used in obtaining a smaller quantity. During the course of taking the readings, however, it was found that the force is at best a rather erratic quantity. The presence of even a slight roughness on the surface of one of the conductors changes the readings a great deal. Furthermore, although the conductors were polished with a cloth at frequent intervals, the accumulation of deposit on the conductors affected the readings, so that they were in a measure dependent upon the time of application of the voltage between each successive reading. For these reasons it is not thought that any detailed conclusions may be drawn from the curves. They do, however, show the existence of a force, its general order of magnitude and manner of variation.

The experimental work which has been briefly described above was entered into in the course of a study of the vibration of small conductors in the laboratory under the influence of high voltage. The most unexpected result shown by the curves which have been presented, is the presence of a relatively strong retarding force at certain speeds of the conductor through the air. Further studies of vibrating spans showed that under certain conditions a span of wire may be unstable and tend to vibrate even though its velocity through the air is such as always to produce a corona force in the direction to retard the motion. The conditions for such vibration, the proof of which is given below, are as follows:

1. The wire must be in a uniform current of air, moving perpendicular to it, of such a velocity that it falls opposite a portion of the force curve which has a positive slope (that is, a portion which shows an increase in the positive value of the force with an increase in air velocity).

2. The magnitude of the slope of the force curve must be greater than the magnitude of the slope of the air resistance curve, at this point. (It is assumed that the air resistance is the only damping force.)

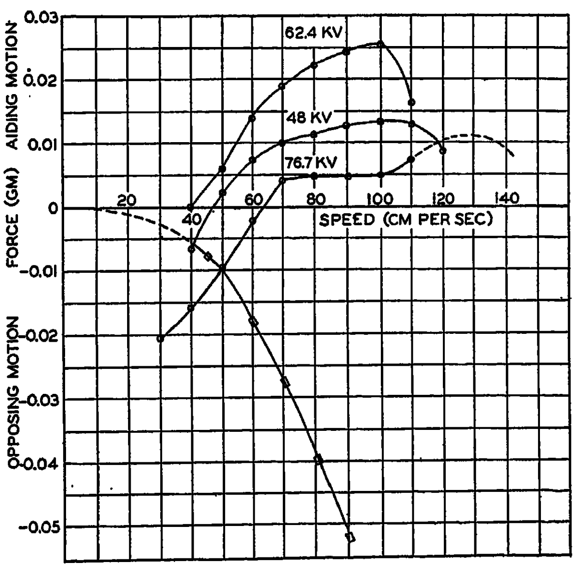

Fig. 6—Speed Force Curves for a 61-Cm. Length of 1.6 Mm. Wire

If these two conditions are fulfilled, the wire will be unstable if vibratory motion is considered to be in a plane parallel to the motion of the air. In other words, for one cycle of vibration the energy input will be greater than the energy output. An analysis leading to a proof of the two conditions above may be given as follows:

Consider a span of wire the length of which is so large as compared with its diameter that the wire may be considered as a flexible string of certain mass per unit length. The natural fundamental frequency of vibration may be easily calculated by means of Lord Rayleigh's formula:

$$f = \frac{1}{2L}\sqrt{\frac{T}{\rho}}, \tag{1}$$

where f = frequency,
L = length,
T = tension,
and ρ = mass per unit length.

If it is further assumed that the wire vibrates harmonically and that its configuration during vibration is a sine wave, it is possible to relate the velocity at any point on the wire at any time, t, with the maximum amplitude at the center of the span. For, considering one point on the wire,

$$V = (\text{max. velocity}) \sin \omega t$$

But the maximum velocity varies over the length of the span

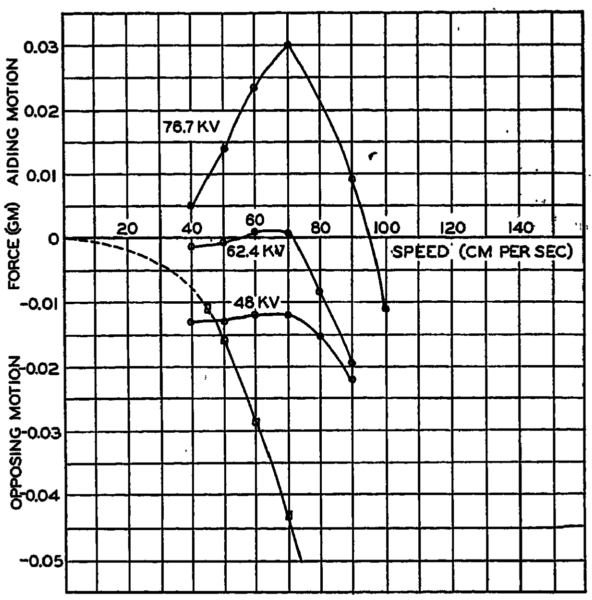

FIG. 7—SPEED FORCE CURVES FOR A 61-CM. LENGTH OF 2.4 MM. WIRE

according to a sine function of the distance, x, from one end. If we let $V = 0$ when $t = 0$, then the displacement will be maximum when $t = 0$, and

$$\text{displacement} = -P \sin \pi x/L \cos \omega t.$$

Therefore

$$V = d/dt\,(\text{displacement}) = P\omega \sin \pi x/L \sin \omega t. \tag{2}$$

It has been shown by Mr. H. L. Richardson and the writer, by means of observations with a stroboscope, that small conductors when vibrating under the influence of high voltage always vibrate at their natural frequencies, and this is to be assumed throughout the following discussion.

The first requisite for a mathematical treatment of the problem is some sort of algebraic equations representing the variation of corona force with velocity, and the variation of air damping force with velocity.

Looking at the corona force and air resistance curves which have already been shown, it is seen first that certain portions of the corona force curves are practically straight lines, for instance, the curve for the 0.8 mm. wire at 76.7 kv. has quite a long straight portion. In other cases parabolas might fit quite well, and there are other possibilities. In the second place, it may be found with a little experimentation that the air resistance curves can be very closely represented by a portion of a parabola, $F = -k_0V^2$.

However, it has been found possible, by assuming general shapes for the corona force curves, such as the straight line $F = mV + C$, to arrive at conclusions which may be applied in a general way to all of the force curves. Actual numerical values need not be used to derive these results, although they may be placed in the results afterward and definite answers obtained.

In general considering a variable force acting upon a moving body,

$$\text{energy} = \int FV\,dt. \tag{3}$$

If the force acts in the direction of motion it will impart energy to the body, or the energy change will be an energy input to the body. The opposite will be true if the force acts counter to the direction of motion.

Now let us assume that the wire is in a uniform current of air of velocity A cm./sec., moving perpendicular to the wire. Also assume that the corona force line may be represented by the general straight line $F_c = mV + C$, and the air resistance curve by $F_d = -k_0V^2$.

In Fig. 8 are shown the F_c and F_d curves; the former is plotted as shown for convenience, but it may take any position depending upon the values of m and C assigned in the equation $F_c = mV + C$. In the lower portion of the figures are shown the direction relationships between the forces involved, during the two halves of the cycle. These relationships hold only when small amplitudes of vibration are concerned, so that *the maximum velocity* (*the velocity relative to the ground*) *of vibration of the wire remains comparatively small as compared with A.* In other words, we are concerned here only with conditions which would render the wire unstable and not with large amplitudes of vibration.

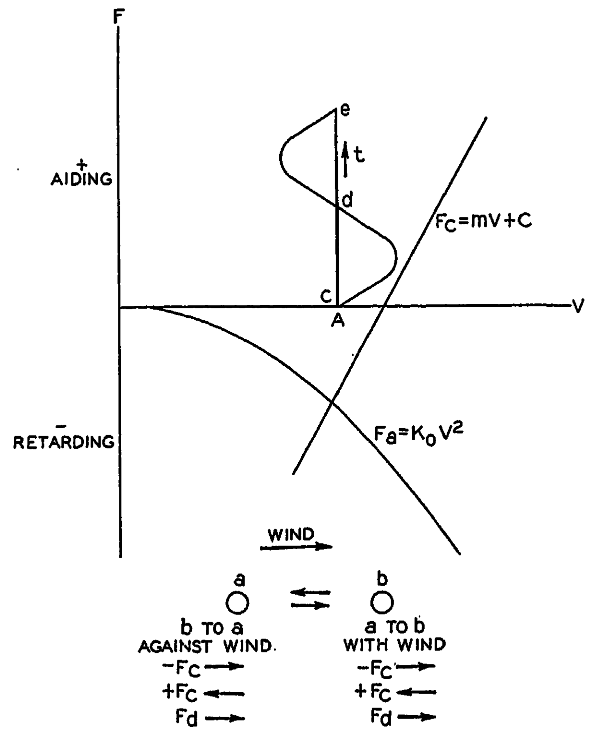

FIG. 8

Referring to the lower portion of Fig. 8, a and b represent the extreme positions of the wire, where its absolute velocity, or velocity with respect to the ground, is zero. The large arrow shows the direction of the wind, and the small arrows below give the directions of the forces which act upon the wire. When moving from b to a, against the wind, a section of the wire is retarded by F_d, and retarded or accelerated by F_c according to the sign of the corona force. When moving from a to b, or with the wind, F_d accelerates the wire as does F_c if it is negative. In other words, a negative corona force tends to decrease the relative velocity of the wire and the air. When the wire is moving with the air, but not as fast as the air, the only way it can do this is to tend to accelerate the wire.

In Fig. 8 is also shown the sine wave of absolute velocity, with the time axis vertical. It is obvious that this velocity curve should be plotted at A, since during one-half of the cycle it adds to the velocity A, giving a velocity $A + V$ relative to the air, and during the other half cycle it subtracts, giving a velocity $A - V$ with respect to the air.

Starting from c and moving to d, on the sine wave of absolute velocity, corresponds to the motion of the wire from b to a in the lower diagram, and from d to e, corresponds to motion from a to b. This is true since motion against the wind increases the relative velocity of the wire and the air, and motion with the wind decreases this velocity.

Now return to equation (3) and consider the signs of the quantities involved. If F is the air resistance force, F_d, its sign will always be negative. Over the first half of the cycle, from c to d on the sine wave, V will be positive and consequently the product, $F_d V$ will be negative and will represent an energy output. During the second half of the cycle, from d to e, both F_d and V will be negative and their product will be positive, representing an energy input.

If F in the equation is F_c, the force due to corona, during the first half cycle the product, $F_c V$, will be positive or negative according to whether F_c is positive or negative. This agrees with what is seen should be true, because as long as F_c is negative it acts toward the right (Fig. 8, lower portion) and retards the motion of the wire. But if the magnitude of A and of the maximum value of V are such that they add up so as to bring the relative velocity to a point on the F_c curve which is positive, or above the axis, F_c shifts its direction and helps the motion of the wire. The same conclusions are true in regard to the second half cycle, only here V is negative and therefore a negative F_c produces an energy input and a positive F_c produces an energy output. Throughout the integration, therefore, the sign of F_c takes care of itself and the result is a net energy change, positive or negative.

Having clearly in mind the fact that a positive sign for the energy in any case represents an energy input and a negative sign, an energy output, we shall proceed to integrate over one cycle to find the net energy due to corona and the net energy due to air resistance.

As the equations for the corona force and the air resistance have been given, the V in each is measured from the origin and represents the relative velocity of the air and the wire. If we take V as the absolute velocity, then the relative velocity becomes $A + V$, where V is the V of equation (2). This amounts simply to shifting the origin on the diagram to the point A. The equations for the two force curves, then, are

$$F_c = m\,(A + V) + C,$$
$$F_d = -\,k_0\,(A + V)^2.$$

Let E_c be the net energy change per cycle due to the corona force, and E_d be the net energy change per cycle due to the air resistance.

Determination of E_c:

$$E_c = \int F_c\,V\,dt = \int (m\,AV + mV^2 + CV)\,dt.$$

Substituting from equation (2) and placing limits,

$$E_c = \int_{x=0}^{x=L}\int_{t=0}^{t=\frac{2\pi}{\omega}}\left(mAP\omega\,\sin\frac{\pi x}{L}\sin\omega t + mP^2\omega^2\,\sin^2\frac{\pi x}{L}\sin^2\omega t + CP\omega\,\sin\frac{\pi x}{L}\,\sin\omega t\right)dx\,dt,$$

$$= \int_{x=0}^{x=L}\left|\left(mP^2\omega\,\sin^2\frac{\pi x}{L}\right)\left(\frac{t}{2} - \frac{\sin 2\omega t}{4\omega}\right) + \left(mAP\omega\,\sin\frac{\pi x}{L} + CP\omega\,\sin\frac{\pi x}{L}\right)\left(\frac{1}{\omega}\cos\omega t\right)\right|_{t=0}^{t=\frac{2\pi}{\omega}} dx,$$

$$= \int_{x=0}^{x=L}\left[\left(\left(mP^2\omega^2\,\sin^2\frac{\omega x}{L}\right)\left(\frac{\pi}{\omega}\right) - 0 - 0 + 0\right) + \left(mAP\,\omega\,\sin\frac{\pi x}{L} + CP\omega\,\sin\frac{\pi x}{L}\right)\left(\frac{1}{\omega} - \frac{1}{\omega}\right)\right]dx,$$

$$= \int_{x=0}^{x=L}\left(mP^2\,\omega\pi\,\sin^2\frac{\pi x}{L}\right)dx,$$

$$E_c = mP^2\omega\pi\,\frac{L}{2} = mP^2\pi^2 fL. \qquad (4)$$

This is independent of A and its sign depends upon the sign of m, the slope of the F_c line.

Determination of E_d:

$$E_d = \int F_d V dt = \int (-\,k_o V^3 + 2AV^2 + A^2 V)\,dt.$$

Substituting from equation (2) and placing limits,

$$E_d = \int_{x=0}^{x=L}\int_{t=0}^{t=\frac{2\pi}{\omega}}\left[\left(-\,k_o P^3\omega^3\sin^3\frac{\pi x}{L}\sin^3\omega t\right) + \left(2AP^2\omega^2\sin^2\frac{\pi x}{L}\sin^2\omega t\right) + \left(A^2P\omega\sin\frac{\pi x}{L}\sin\omega t\right)\right]dx\,dt,$$

$$= -\,k_o\int_{x=0}^{x=L}\left|P^3\omega^3\sin^3\frac{\pi x}{L}\left(-\frac{1}{\omega}\cos\omega t + \frac{1}{3}\,\omega\cos^3\omega t\right) + 2AP^2\omega^2\sin^2\frac{\pi x}{L}\left(\frac{t}{2} - \frac{\sin 2\,\omega t}{4\omega}\right) - A^2P\sin\frac{\pi x}{L}\cos\omega t\right|_{t=0}^{t=\frac{2\pi}{\omega}} dx,$$

$$= -\,k_o\int_{x=0}^{x=L}\left(\frac{\pi}{\omega}\right)2AP^2\omega^2\sin^2\frac{\pi x}{L}\,dx,$$

$$= -\,k_0\,2AP^2\omega\pi\int_{x=0}^{x=L}\sin^2\frac{\pi x}{L}\,dx,$$

$$= -\,k_o\,2AP^2\omega\pi\left|\frac{x}{2} - \frac{\sin^2\frac{\pi x}{L}}{4\pi/L}\right|_{x=0}^{x=L}$$

$$= -\,k_o\,2AP^2\omega\pi\,\frac{L}{2} = -\,k_o\cdot 2AP^2 fw^2 L. \qquad (5)$$

Equations (4) and (5) give the expressions for E_c and E_d over a complete cycle of vibration for the whole wire, under the conditions which have been assumed in this case. If m in the equation for the corona force line is positive, the net energy due to corona is an energy input to the wire; if m is negative the energy is an energy output. The net energy due to air resistance is always an energy output, since k_o is always negative.

Now let us take the ratio of the magnitude of E_c to the magnitude of E_d.

$$\frac{|\,E_c\,|}{|\,E_d\,|} = \frac{mP^2\pi^2 fL}{k_o\,2AP^2\pi^2 fL} = \frac{m}{2\,k_o A} \qquad (6)$$

The slope of the corona curve, as has already been stated, is

$$|\,S_c\,| = m\,. \qquad (7)$$

The slope of the air resistance curve is

$$S_d = dF_d/dV = -\,2\,k_o V,$$

and its slope at the point A is

$$S_d = -2\,k_o A.$$

Or since the slope is always negative, taking the magnitude only,

$$|S_d| = 2\,k_o A. \tag{8}$$

Substituting (7) and (8) in (6),

$$\frac{|E_c|}{|E_d|} = \frac{|S_c|}{|S_d|} \tag{9}$$

Therefore, under the conditions assumed, the question as to whether or not the wire will vibrate depends only upon the relation between the slopes of the two curves for F_c and F_d at the point A. Since the sign of S_c determines the sign of E_c, the two conditions which must be met in order that the wire may be in an unstable state and tend to vibrate are those stated above. A numerical example follows:

Taking the corona force curves for the 0.8 mm. wire, and considering the curve for 76.7 kv. in particular, it may be found that the straight portion of this curve, *i. e.*, from about 69 cm./sec. to about 115 cm./sec. has a slope $m = S_c = +0.000778$ and that the constant in the equation of the air resistance curve is $k = 3.5 \times 10^{-6}$ both in grams per cm. per sec.

Assuming an 0.8 mm. copper wire 30 ft. (= 915 cm.) long with a tension of 5 lb. the calculation of the fundamental frequency of vibration by means of formula (1) may be easily made, and the result is: $f = 3.8$ cycles/sec.

Also assume

$P = 1$ cm.

$A = 1.5$ miles/hr. $= 67.2$ cm./sec.

(If $P = 1$ cm., $P\omega$ = max. absolute velocity $= 1 \times 2\pi \times 3.8 = 22$; this is well under A, and therefore the assumed condition is fulfilled.)

The length, L, in the formulas for E_c and E_d, is "unit" length, or the unit of length of the wire for which the force on the curves was taken. The unit length in this case is 61 cm. Therefore the expressions for E_c and E_d must be divided by 61. Also since force is given in grams, the units of E_c and E_d will be in joules $\times \frac{10^7}{980}$. Therefore, in order to obtain joules in this case we must multiply by $\frac{980}{10^7}$.

Then

$$E_c = \frac{mP^2\pi^2 FL}{61} \times \frac{980}{10^7} = \frac{0.000778}{61} \times 1 \times \pi^2 \times 3.8 \times 915 \times \frac{980}{10^7} = 0.0000431 \text{ joules}$$

and

$$E_d = \frac{-2k_oAP^2f\pi^2L}{61} \times \frac{980}{10^7} = \frac{-2}{61} \times 3.5 \times 10^{-6} \times 67.2 \times 1 \times 3.8 \times \pi^2 \times 915 \times \frac{980}{10^7} = -0.0000260 \text{ joules.}$$

The energy input per cycle is, then, 0.0000431 joules, and the energy output per cycle is 0.0000260 joules. A maximum amplitude of 1 cm. was assumed for convenience. Obviously, for this same value of A, regardless of amplitude E_c will always exceed E_d, as shown by the equations. But the corona force curve is a straight line only within very definite limits and therefore the amplitude would not increase very much beyond 1 cm. before the energy input would fall off very quickly. We cannot predict the maximum amplitude from these results, over the range covered, but we can say that the wire would tend to vibrate under these conditions.

If A were taken still larger, the difference between E_c and E_d for any amplitude would be less, and finally if A were taken opposite the point where the two slopes are equal, E_c would equal E_d and the wire would not vibrate.

E. W. Dillard: Messrs. Davison and Monroe have described in detail two commonly recognized types of conductor vibration which are now familiar to many engineers. Mr. Monroe has also briefly touched on a third type of vibration with which we have had some experience in New England. Although this vibration has been shown to be harmless, it has aroused considerable interest because of its apparently close relation with the phenomenon of corona.

This phenomenon was first observed on the 220-kv. Fifteen Mile Falls transmission line during a snow storm a few weeks after the line was put in operation. Subsequent field tests established the following facts, which seemed to indicate that its origin was different from that discussed in the two papers mentioned above:

1. Vibration occurred only when the line was energized.
2. Vibration occurred only under atmospheric conditions where either fog, rain, or wet snow were present.
3. Vibration occurred only when the wind velocity did not exceed three miles per hour, and most cases occurred with a lower value.
4. The character of the vibration is different from either of the well known types. In amplitude, wave length, and frequency it lies between "wind vibration" and "galloping." The frequency is of the order of 75 cycles per minute with corresponding loop length.

The presence of voltage as a necessary condition was thoroughly demonstrated by the field tests which have been confirmed by subsequent observations. Vibrations die out within fifteen minutes after the line is deenergized and build up in about twenty minutes after sufficient voltage is restored. The presence or absence of current flow is apparently of no significance. Furthermore, the field tests indicated that there is a critical voltage below which vibration will not take place even during the most propitious conditions.

The Fifteen Mile Falls transmission line has been fully described in the September 6, 1930 issue of the *Electrical World.* The line consists of two circuits, 795,000 cir. mils aluminum, on single-circuit towers. It was definitely designed for a low normal tension in the conductors and a low average height above ground which resulted in a normal tension of 2,900 lb. and the use of 8.94 towers per mile. The insulation consists of 15 disks with grading rings. Tapered armor rods were installed to further protect the conductors from burning and from mechanical injury at the clamp. It is believed that the low conductor tension and the damping action of the armor rods greatly reduce the possibility of fatigue failure from high frequency wind vibration of the type described in the preceding papers.

An analysis of the field tests led to the belief that disruptive corona might be a third cause of vibrating conductors. A test span, the exact duplicate of one of the spans on the line, was erected to confirm this hypothesis by further experiments under controlled conditions. Power was supplied from a single-phase 300-kv. grounded neutral testing transformer, and a row of sprinklers installed above the span provided a means of supplying precipitation at will.

It was found that no vibration could be produced if the wind velocity exceeded four miles per hour. Difficulties were experienced in carrying on the tests because of the fact that wind velocities are usually greater than this limit excepting for very short periods at sunrise and at sunset. We also found that vibration will occur with a lower voltage during precipitation than when the conductor is dry. This explains the rare occurrence of vibration on the line since the simultaneous conditions of low wind-velocity and precipitation are required.

Under the test conditions we were able to produce vibrations in all sizes of conductors from No. 14 A.W.G. stranded copper

antenna wire to 795,000 cir. mils A.C.S.R. Fig. 9 shows the relation between the voltage required to sustain vibration and the conductor diameter. Within the precision of the set-up the points fall on a smooth curve which closely resembles the "storm corona" voltage curve which is plotted in the same figure. A single exception was encountered. We were unable, with the voltage available, to produce vibration in a No. 4/0, seven-strand, hard drawn copper conductor which seemed to have inherent mechanical characteristics which suppressed any tendency toward vibration.

On the smaller sizes of wire; that is, up to No. 4 A.W.G., it was possible to cause vibration without any precipitation; that is, when the wire was dry. On the larger sizes of copper and aluminum cables precipitation was necessary with the voltages available. In the case of the smaller wires, where voltage enough to cause vibration in the dry state was available, vibration took place at voltages about twice the voltage necessary for vibration when wet.

In general, the amplitudes which were developed in the test span were less than those reported on the line under operating conditions. This is probably accounted for by the relative length of span. In one case, however, an amplitude of 40 in. was obtained by impressing 235 kv. on a No. 4 A.C.S.R. when dry.

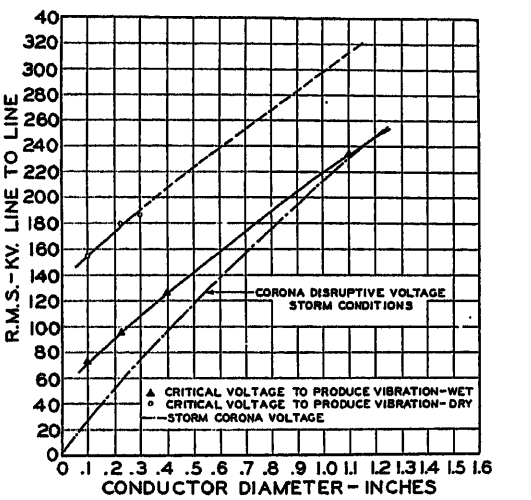

Fig. 9

Vibrations appeared to build up slowly after the application of a voltage higher than the critical voltage; ten minutes to half an hour (depending upon the conductor size) were required before the final steady state was established. For voltages only slightly higher than the critical voltages the motion is likely to be a short traveling wave, approximately one-twentieth the span length, and it is reflected at the points of support. At higher voltages the motion is more likely to take the form of a standing wave with nodes usually not less than 20 ft. apart. When standing waves are established, an increase in voltage causes an increase in amplitude and, frequently, an increase in wavelength together with a decrease in frequency.

The Subcommittee on Conductor Vibration of the Pacific Coast Electrical Association reported, *Electrical West*, May 15, 1930, a case of vibration on the California-Oregon Power Company system which very closely resembled that noted on the Fifteen Mile Falls line. Correspondence with the engineering department of this company has developed the fact that vibration occurs on the two transmission systems under identical conditions. The voltage of the California-Oregon line is 120 kv. and the conductors are No. 2/0 copper. The vibration point of this conductor is closely checked by the results which were obtained in the New England test span.

It is believed that the foregoing data indicate the following new principles in regard to conductor vibration:

1. Any line which is subjected to voltages above the storm corona limit may develop vibrations.
2. Such vibrations are not caused by wind pressures; on the contrary, the presence of even moderate velocities of wind suppresses the tendency toward motion.
3. It is probable that the formation of corona is closely allied with the forces producing vibration.
4. That such forces can exist is clearly shown in the cooperative investigation made by Messrs. Basinger and Richardson of the Massachusetts Institute of Technology whose results are presented in a separate discussion.
5. Frequent vibration of this type is unlikely since it usually occurs only when there is precipitation and never when there is any appreciable wind.

We feel that the possibility of damage from this type of vibration on the Fifteen Mile Falls line is practically negligible. The unusually low stringing tension that was used in the design of this line is a preventative to wind vibration, and armor rods were also installed as a further safeguard against any incipient motion or arcing. Vibration from corona is of such rare occurrence and low frequency that lines with materially less favorable characteristics should not be affected adversely.

We do not feel that our investigation has been exhaustive and it is desirable for academic reasons that it be supported by further observations and experiments. It is urged that all engineers operating transmission lines at or near the limiting corona voltage be particularly watchful for vibrations of this type, especially during periods of precipitation when wind is absent or of low velocity.

L. L. Perry: March 21, 1932 in Illinois and Indiana was an extraordinary day in weather. Conditions produced sufficient dancing of conductors to trip out 132-kv. circuits of both A.C.S.R and copper. Circuits tripped out at points about 130 miles west of Chicago, a few miles south of Chicago, and at a point about 150 miles east of Chicago.

At Chicago the total temperature range was only from 29 deg. F. minimum to 30 deg. F. maximum, with a maximum wind of 35 miles per hour. At one point in Illinois four parallel circuits of 447,000 A.C.S.R. on 2 two-circuit tower lines tripped out within a few seconds of one another when the nearest weather bureau station recorded 19 miles per hour wind, slight rain, freezing, a temperature 31 deg. F. to 30 deg. F., with a range over the day from 32 deg. F. at 1:00 a.m., to 28 deg. F. at midnight.

Apparently all these trip-outs occurred at one point, as evidenced by burns on the conductors and ground wires. At this point, this transmission has a diagonal run that presented the only case of about 90 deg. angle of line with the wind. The circuits danced less in other spans, but gave no evidence of tripping out. Sleet thickness was estimated at 3/8 in. radial. The Springfield, Illinois, weather bureau records read: "From LaSalle south as far as Carlinville the day produced almost everything in the way of weather, *viz.*, rain, snow, sleet, glaze, wind and thunder."

In Alabama that day the tornados, numbering 7, were the worst on record. Since the weather bureau report states that "a bounding tornado" was reported in Illinois with a path 25 to 50 ft. wide, striking the ground intermittently, it is fair to assume winds may easily have been spotty.

The first 132-kv. line in the Chicago District went into service in 1924. This circuit was 300,000 cir. mil copper strung to rather low tension on 500 ft. spans. Very little lightning disturbance occurred in 8 years in that transmission, and none that would prevent the circuit immediately being closed and kept in after trip-out. This line gave no dancing difficulties until about 5 years had elapsed, and then only momentary interruptions resulted. But after another year, however, a day came when interruptions were so frequent that one circuit was kept out of service for some hours.

Commenting on Mr. Monroe's claim that dampers would not be injured by dancing: why then are insulators injured by dancing conductors?

J. A. Ingles: Discussions, such as Mr. Den Hartog's, of vibrations resulting from sleet load or other causes are very opportune. It is highly desirable that this phenomenon be kept prominently before transmission engineers and executives, since there is no convenient method of controlling the hazard and the interruptions in the service, which may be expected. About the only known remedy is to keep the cables warm by artificially heating them slightly above surrounding temperatures during sleet forming periods. We know that this method is effective. The paper does not offer any suggested remedial measures.

While admitting that the so-called "galloping" due to sleet and other causes, is a vibration and is associated with all other vibration phenomena, efforts have been heretofore made to segregate, if possible, in the minds of those who have not studied the matter extensively, the considerable differences which there are between the problems of controlling interruptions and failures due to this "galloping" and the troubles which develop on account of the finer vibrations. Conditions which result from sleet loading and winds at 5 to 15 miles per hour, cannot very well be imagined. They have to be seen in the field. "Galloping" so-called of various conductors, including small telephone wires, is fairly frequent in the district of 100 miles radius centering on Niagara Falls. It is not peculiar to that district.

Mr. Den Hartog quite correctly points out that in earlier references to "lift," "drag" studies were omitted and that it is desirable to study the resultant forces at the various angles which the flopping cable may present to the wind. Vibration is always extremely fortuitous and almost anything can happen if the combination of long icicles and moderate winds continue, for a very long time.

Referring to Mr. Stickley's paper, it has been known for some considerable time that a cable when strung takes some time before reaching its final sag conditions. The reason for this is made quite evident in the paper.

Mr. Stickley presents the view that tension in the cable tends to wrap the strands of the various layers closer together. It would be interesting to know if during tests, he has experienced any basketing or "birdcaging" of the cables, for instance, as at end conditions or connections, as indicated by Dr. Ing. T. Gröble, or if he has taken any record of the rotation of the cables under test.

On the question of vibration, it would be most advantageous to tabulate the fatigue limits of the various metallic cables. Vibration failures are largely due to combined stresses exceeding a safe limit. Until recently the only indication that these stresses were exceeded was the fact that failures occurred. With Stickley's values of a cable a fairly reasonable value of stresses could be calculated. Then reference to some authorative tabulation of fatigue limits, or fatigue curves, should be made to enable the designer to know whether he is within safe limits or not. The fatigue limit is in every way as important as the ultimate stress of a cable and it would be to the advantage of the transmission engineer if these values could be published by the manufacturer.

M. E. Noyes: The suggestion is made by Messrs. Davison, Ingles and Martinoff that different types of stranding of cables should be compared to determine their relative ability to dissipate energy by interstrand friction. The Aluminum Company of America has done this successfully in its laboratory on 120 ft. spans using a decrement method suggested by Mr. Kimball, of General Electric Company. The decrement of amplitude is measured from a trace taken after the source of forced vibration has been suddenly disconnected from the cable. This value of decrement is then substituted in the Kimball formula.

In considering new cross section shapes and new types of stranding as means for reducing amplitude of vibration, it is very important to remember that no mathematical or laboratory study has taken into account the importance of severe stress concentrations which may occur at the ends of the span due to abrasions of the surfaces of the wires. The result of surface deformation is commonly called "notch effect" when encountered in laboratory testing for fatigue of metals. It is well known that a surface indentation produces a concentration of stress which greatly lessens the life of the fatigue test specimen. For transmission line conductors we must not overlook unavoidable localized stresses, from this cause, at the supporting points. Any cross-section shape of conductor which causes certain strands to stand out sharply would, in my opinion, be liable to higher stress concentrations than the usual round cable.

E. Bate: The paper by Messrs. Davison, Ingles and Martinoff is devoted principally to a comparison of effects produced by deliberate departure from the conventional cylindrical form of conductors, the intention being to prevent or minimize the production of eddies identical in phase or period. This is a very sound line of attack on the problem, since it aims at a diminution of the energy which can be transferred to the conductor by the wind. The converse problem is to increase the resistance of the conductor to bending, *i. e.*, to increase greatly its ability to dissipate energy and so reduce the amplitude of vibrations.

To both of these problems the writer, together with many other engineers, has directed some effort, and in the case of the former problem an attempt is at present in progress to determine the wind energy input without resource to water experiments. Even in the case of a cylindrical conductor this is a somewhat difficult matter, though once determined, formulas can be developed for similar conductors. In the case of freak shapes there seems to be no alternative but to attempt to solve each case by experiment.

Unfortunately, very few freak sections appeal to the engineer as practical or economical, especially if alternative means of suppression can be satisfactorily applied. There is, nevertheless, a possibility that assiduous trial may lead to a radical change in present conventions.

It must be admitted that our present estimate of the danger to be apprehended from vibrations of a given wavelength and amplitude for a given conductor, stressed to a predetermined extent, is vague, so that it is difficult to determine the influence on the life of the conductor of any percentage reduction in amplitude, or whether at some point short of complete suppression a condition of indefinite life is reached. The rationalization of these questions to a state where they are susceptible of calculation would greatly inform the minds of transmission engineers.

Strand failure due to fatigue resulting from vibration is not confined to A.C.S.R. conductors. In the writer's experience steel cable though lightly stressed has given much trouble, in short, every cable must be considered in the light of its inherent characteristics and the conditions to which it may be exposed. At present the decision or design depends too greatly on judgment.

In addition to the two directions above mentioned in which a diminution of vibration is to be sought, there is another important provision which can be made—namely dampers of various kinds. A purely frictional device may be used in lieu of inherent damping in the cables, though most of those proposed are clumsy and unsuitable for use on transmission lines.

It should be possible, however, to devise an arrangement which, actuated by the initial movements of the cable before full resonance is attained, generates and allows to be reflected along the span, an interfering wave, which causes an immediate reduction in energy input to the conductor by the wind.

In the ideal state, when resonance is building up on the span, a complete set of loops, practically sinusoidal in shape is formed. This condition is essential for maximum energy transfer, and the energy transferred will then vary directly as the amplitude of the oscillation. If, however, this symmetrical sinusoidal arrangement be upset by interfering waves, it may be possible

to reduce the magnitude of energy transfer, and so inhibit resonant oscillation. To such interference the transmission span is very susceptible in view of the minute quantities of energy involved.

An action such as this, is the cause, in the writer's opinion, of the efficacy of one or two of the services or arrangements which are used and designated as dampers. Experiment shows that they could not be expected to dissipate in friction sufficient energy justly to account for the great reductions in amplitude which they cause.

V. M. Martinoff: The users of transmission materials and conductors appreciate the great amount of work which Messrs. Monroe and Templin, and their associates, have done, and as well the cooperation which has been manifested where problems have arisen.

Reference is made to the relative life of certain materials when used at 15,000 to 18,000 lb. This is only a small variation but it would seem that the life has been materially altered. Speed-up tests probably increased the elastic hysteresis in the cable as compared with natural conditions and probably reduced the life of the cable considerably. Is there any information available to prove or disprove quantitatively this statement?

As the experimental determination of the flexural rigidity of cables at discontinuities is of great importance, I would like to ask the writers if they know an empirical equation by means of which an approximation of section modulus of a stranded cable may be obtained at various distances from the clamp. Have any experiments been carried out to determine such an equation?

Have the experiments differentiated between the effects of winds blowing at the more acute angles to a conductor under observation as compared with perpendicular light winds? Were there any curves obtained showing variations in amplitudes for winds of equal velocity but blowing at different angles to the line?

A. E. Davison: It is desirable in case further studies of vibration are made that someone prepare a statement for the direction of other engineers covering as near as possible all those factors which affect vibration and fatigue tendencies, both adversely and beneficially, discuss each briefly and correlate them as to importance.

It is thought by some that the direct and immediate solution would be by way of minor reductions in the economics of a transmission system—that is, add some 2 to 5 per cent to the cost of a transmission system and thereby reduce the mechanics in the conductor by as much as 25 or more per cent.

Apart from this which is an entirely economic feature, some of the adverse factors are:

1. *Location of Line with Regard to Terrain.* Open, level areas, free from wind obstructions such as trees, buildings and hills probably give rise to excessive fatigue on account of heavier vibration.

2. *Relative Smoothness of Surface of Conductors.* It is assumed in this connection that a thoroughly polished and perfectly round cylinder would provide maximum opportunity for the effects which a given wind might have on vibration.

3. *Wind Velocity.* Low wind velocities give rise to approximately stream line flow, and formation of steady eddies in lee of cable. High velocities give turbulence disrupting the eddies. There is probably a critical velocity giving the worst fatiguing effects.

4. *Wind Uniformity.* Non-uniform winds give rise to beats which are probably more serious than uniform vibration. Turbulence as pointed out above may be beneficial in that vibrations could be broken up.

5. *Length of Cable Without Discontinuity Which Could Act as a Reflector, Thereby Introducing a Source of Fatigue.* Where long spans are used, larger amounts of energy are carried to the clamps.

The word "discontinuity" is used to cover splices as well as suspension clamps and other points of attachment. This would require a discussion on methods of suspension, etc.

6. *Tensions.* Higher tensions increase both direct and bending stresses, therefore tend to produce fatiguing more rapidly.

7. *Fatigue or Endurance Limit of Metals Used in Conductors.* What are the correct limits to use for various metals? It may be assumed that most conductors in present practise are stressed beyond the fatigue limit. Is any one type of metal or alloy better than another? Resilience limits require attention.

8. *Load per Clamp.* Should double suspension or double clamps be used to reduce combined stresses so that they will be within fatigue limits?

9. *Inertia of Cable.* Resists setting up of vibration but tends to sustain it once it is built up. Extremely light weight cables if pulled to unnecessarily high tensions should account for generation of greatest mechanical energy.

10. *Resonance Point of Cable or System.* If resonance point can be moved outside governing practical limits, vibration will be overcome. (See Ferrier.)

11. *Diameter of Cable, That Is, Exposure versus Mass.* Frequencies also are inversely proportional to diameters.

Among some of the beneficial factors are:

1. Fatigue resisting qualities of metal used—toughness, etc.

2. Internal friction—interstrand and stiction (static friction). What are the relative damping qualities of each?

3. Viscosity of medium in which cable is vibrating; "head" and "dynamic" resistances.

4. Size of strands making up cable. Distribution of stress in small as compared with large strands. Large strands give irregular profile.

5. Variation of surface from standard round rod.

It is desirable that someone who is interested in the subject give some attention to the analysis and weighting of these and other factors.

Messrs. Andrews and Eddy submitted that "disturbance (greater than ½ inch amplitude) cannot arise without ice," and ask that the statement be checked.

The facts submitted by Mr. Dillard in his discussion confirm the general statement that relatively long catenaries are naturally quite too unstable to limit causes of major vibrational disturbances to glaze, although glaze may account for a very large part of the associated interruptions and their duration.

The horizontal vibration which Mr. Monroe mentioned at Cleveland and vibrations associated with corona as described by Mr. Dillard are phenomenal, but as Mr. Dillard suggests are not sufficiently frequent, as yet, to be considered troublesome.

All vibration curative and preventive measures for various types of vibrations of relatively small amplitude, can scarcely be expected, as Mr. Andrews infers, to solve the troubles associated with glaze, and frequently called galloping or dancing.

Until the latter part of 1932, little had been heard of that type of vibration described by Mr. Dillard. Recently a patrolman called in quite disturbed, saying that on a damp dull afternoon he observed wires which were subject to the ordinary fine vibrations, demonstrating extraordinary amplitudes of the order of 3 or 4 inches. His statement was "approaching galloping," with which phenomenon he was familiar. Conditions did not continue long enough for any one other than the patrolman to observe the phenomenon.

Mr. Dillard's statement that they were unable with the voltage available to produce vibration in No. 4/0, 7-strand, hard drawn copper conductor which seemed to have inherent mechanical characteristics which suppressed any tendency towards vibration, is intriguing. Considerable attention has been given here to relative susceptibilities.

It is desirable that Mr. Dillard, or another, follow up this peculiarity, because it is felt that such fortuitous phenomena as vibration may be checked and wholly cured by some minor

inherent mechanical or other characteristic yet to be discovered.

Suggestions made by Mr. Noyes regarding deformed conductors are quite opportune. Very little attention is being given to splicing methods, clamping surface and such details until it is recognized that the suppressing effects are of sufficient magnitude to warrant extra expense in connection with such details. The study is not completed.

Concluding the writer wishes to thank those who have given a great deal of attention to this subject by way of discussion. There is, doubtless, sufficient material in some of the discussions for separate papers, but for the fact that the discussors were anxious to place the information before interested engineers and operators, who have recognized some of the problems.

G. W. Stickley: Referring to Mr. Ingles' discussion, we have never experienced any basketing or "bird-caging" of cables during stress-strain tests. The testing procedure and the care necessary in making such tests practically eliminates the possibility of such occurrences. Rotation of the cable test specimen during any test was not possible because only one head of the testing machine was free to move, and that one could move in one direction only.

R. A. Monroe and R. L. Templin: In the discussion several questions have been raised which can be definitely answered only after further investigational work. This paper was intended as a progress report showing the results of work done to date, and it is planned to present the results of further investigations later.

Two problems discussed were not covered in our investigational work, namely, the phenomenon generally known as "dancing," which was discussed in a separate paper by Mr. Den Hartog and the vibration occasioned by corona, which was discussed from the theoretical and practical standpoint by Messrs. Basinger and Dillard.

Certain direct questions have been asked relative to the data and formulas presented in our paper, some of which can be answered in the light of present information.

Mr. Koontz states that he prefers using four dampers at a staggered spacing for any conductor of 1 in. diameter or larger. Our experience has been that, with cable of sizes up to 795,000 cir. mils (1.1 in. diameter) A.C.S.R., one damper at each end of the span at equal distances from the supports will satisfactorily damp vibration. Considerations of economy would dictate the use of only two dampers instead of four, providing the damping is satisfactory. The use of four dampers is, however, frequently necessary on spans exceeding 1,000 ft. in length.

The question raised by Messrs. Andrews and Eddy concerning equation (1) is explained by the statement that L is the loop length rather than the wave length and is expressed in inches instead of feet, whereas g is in feet per second.

Mr. Perry's question as to why we believe that dampers would not be injured by dancing whereas insulators are frequently broken may be answered as follows: The insulator is firmly attached to a stationary tower and consequently has to withstand the impact resulting from the reversal of the motion of the entire mass of the vibrating cable. The damper, being attached to the moving line, is free to move with it; its mass is also small and the stress due to any differential motion between the cable and the damper cannot be large.

With reference to the first question raised by Mr. Martinoff relative to the effect of tension on the life of the cable, a comprehensive series of tests is now in progress which will cover this subject more completely than was possible in the paper. A further study of the flexural rigidity of cables is also in progress. It has been found that if the component of the wind normal to the cable is used, the theoretical and observed frequencies agree satisfactorily. The relation between amplitude and wind direction, if any exists, has not been determined.

Many of the subjects listed by Mr. Davison are being studied in the investigational work which we now have in progress and it is hoped that we will be able to cover them in future papers. Undoubtedly other investigators will cover the other factors mentioned.

In conclusion, the authors wish to express their appreciation of the interest with which their paper has been received and to thank all of those who have contributed to the discussion.

J. P. Den Hartog: The model shown in Fig. 10 was built since the writing of my paper and was demonstrated at the Cleveland meeting. On the left, clamped to the laboratory stand is the Lanchester tourbillion, carefully constructed with a small ball bearing and a spring clamp on its face into which

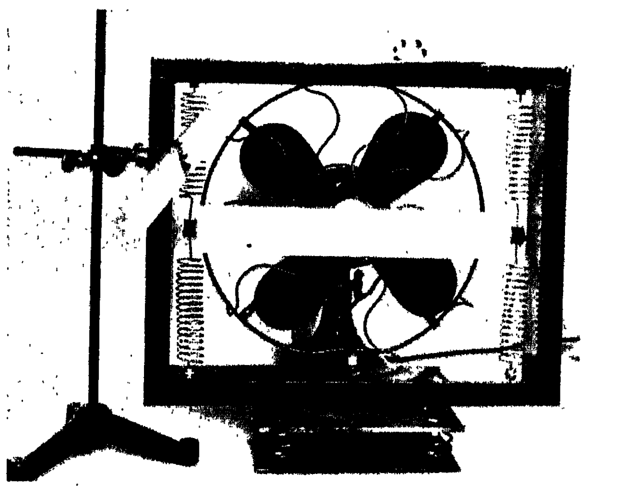

FIG. 10

wooden models of various cross sections can be inserted. In the illustration a semi-circular section is shown. Placed in front of an ordinary fan the various sections behaved in conformity with the theory.

To the right a wooden section is suspended in springs in a heavy steel frame, thus creating a vibratory system quite similar to a short section of the galloping transmission line.

A semicircular section in this apparatus placed in front of the fan will build up vibrations of two diameters amplitude in a few minutes. Other sections, like the rectangular one for instance require the air stream of a wind tunnel to make them respond.

The difficulty in making a model of this kind is to keep the damping sufficiently small. This has been accomplished by soldering the joints of the springs with careful fillets, and moreover by mounting the whole frame on springs again. In the absence of these latter springs the frame will vibrate the table on which it is placed and thus destroy the effect. Besides offering a rather striking demonstration the model has given a complete verification of the theory propounded in the paper.

Research

ANNUAL REPORT OF THE COMMITTEE ON RESEARCH*

DURING the year 1931 the Committee on Research has encouraged the presentation of research papers and has reviewed many for sessions on research before the A.I.E.E. On account of the broad field which must be covered by this committee it has been impracticable to organize subcommittees under any specific classification. The burden of reviewing papers has fallen to practically all members and excellent cooperation has been obtained by correspondence and without committee meetings.

The following topics are worthy of mention to show the progress that has been made during the year. The subjects reported have all been suggested by committee members.

Physics

Dr. R. J. Van de Graaf of Princeton University and Massachusetts Institute of Technology has developed static machines of a very simple construction using endless silk belts with which he has generated as high as 1,500 kv. This work is being extended to much higher voltages.

Dr. F. Lange and A. Brasch of the University of Berlin have built a simple X-ray tube consisting of alternate rings of paper, rubber, and aluminum which they hope to operate with voltages up to 2,500 kv.

A number of developments have taken place during the year in connection with X-ray tubes and auxiliaries. Some of these are described in the January issue of the *General Electric Review*. The application of X-rays commercially has been extended during the year to the sterilization of food and food products.

Experiments have recently been made in this country on a sodium vapor lamp, originally developed in Germany. This lamp has been made possible by a new kind of glass which is not blackened by the sodium vapor. This lamp is said to be several times as efficient as the ordinary mercury or gas filled lamp.

In ferro-magnetic materials changes in magnetization do not occur instantaneously throughout the mass of the material, but start locally and are propagated with finite velocity. This was demonstrated on a large scale by K. F. Sixtus and L. Tonks and the velocity of propagation was measured in nickel-iron wires under tension. (*Physical Review*, 37, 1930, p. 1958, April 1931.)

From the Westinghouse Laboratories a new magnetic phenomenon has been reported by F. Bitter, which consists in the discovery of magnetic inhomogeneities of a definite and regular pattern in the individual crystals of ferro-magnetic materials. These are of quite a different nature, depending on the type of material. No satisfactory explanation has yet been obtained for this phenomenon.

Members of the staff of the Alabama Polytechnic Institute have announced the discovery of the last missing element, No. 85.

From theoretical considerations, it was believed that atoms of hydrogen might exist which are twice as heavy as the ordinary atoms. These have now been discovered experimentally by H. C. Urey and G. M. Murphy of Columbia University and F. G. Brickweede of the Bureau of Standards.

Walter Bathe is reported by A. H. Compton to have produced gamma rays by bombarding beryllium metal with alpha rays. His experiments indicate a possible synthesis in which a heavier element, carbon, is formed and if proved correct it may greatly affect all ideas of how the solar system and our earth originated. (*Sc. News Letter*, p. 223, Nov. 21, 1931.)

Vacuum tubes are continually extending the ranges of possible electrical measurements and thereby opening new fields of physical research. L. A. DuBridge (*Physical Review*, Vol. 37, page 392, 1931) reports measurements of small currents of the order of 10^{-18} amperes which corresponds to six electrons per second.

Fowler (*Physical Review*, Vol. 38, page 45, 1931) has made important theoretical investigations of the photoelectric threshold values of clean metals at various temperatures.

Newton Harvey (*Jl. of General Physiology*, Vol. 15, p. 147) has demonstrated that living cells are disintegrated by ultra-sonic waves in less than $^1/_{1000}$ of a second.

R. W. G. Wyckoff (*Radiology*, Vol. 17, p. 1171, 1931) has obtained important data on the destruction of micro-organisms by X-rays and cathode rays in continuation of his previous work in this field.

Boer and Teves (*Zeitsch. f. Phys.*, Vol. 73, page 192, 1931) have obtained further important results in connection with their investigation of the photoelectric properties of caesium oxide films in conjunction with halide salt layers.

Bergmann (*Zeitsch. f. Phys.*, April 1, 1931) has described an important photoelectric cell involving essentially the photoelectric properties of iron selenide.

Dielectrics

The Committee on Electrical Insulation of the Division of Engineering and Industrial Research of the National Research Council reports very substantial progress in the study of dielectrics and dielectric phenomena. Its report, which summarizes a considerable number of recently presented papers, should be consulted by those interested in this subject. The following items, some of which were reported by the National Research Council, are of par-

* COMMITTEE ON RESEARCH:

L. W. Chubb, Chairman,		
H. D. Arnold,	W. P. Dobson,	H. H. Race,
Edward Bennett,	F. M. Farmer,	C. W. Rice,
W. G. Cady,	V. Karapetoff,	D. W. Roper,
E. H. Colpitts,	A. E. Kennelly,	T. Spooner,
E. C. Crittenden,	J. K. McNeely,	J. B. Whitehead,
W. F. Davidson,	F. W. Peek, Jr.,	R. J. Wiseman.

ticular interest. Some of these results have been presented in the form of papers before the Institute.

A further reference which may be consulted with profit to those interested is monograph No. 5 of the American Chemical Society, by Professor C. P. Smythe of Princeton University, giving an extensive summary of the results of the work in determining molecular structure.

The following four A.I.E.E. papers from The Johns Hopkins University on this subject by Dr. Whitehead and his associates are particularly valuable, namely, on the *Conductivity of Insulating Oils*, *The Fundamental Properties of Impregnated Paper*, *Residual Air and Moisture in Impregnated Paper*, and *The Predetermination of the A-C. Characteristics of Dielectrics*. Other valuable A.I.E.E. papers on dielectrics are *Insulation Variability*, by M. C. Holmes; *On the Theory of Thermal Breakdown of Solid Dielectrics*, by P. H. Moon, and another in the same field by Kenney, Luery, and Moriarty.

In one of the above mentioned papers by Whitehead and Banos there is announced a most remarkable agreement between loss, power factor, and capacity values at 60 cycles for solid and liquid dielectrics as determined experimentally and as calculated from the d-c. characteristics as obtained by the oscillograph.

By very careful distillation and purification as reported by L. A. Welo it has been possible to produce insulating oils having conductivities of 10^{-18} to 10^{-19} ohms.

The Bell Telephone Laboratories have reported very interesting results on ordinary insulation in which they point out that it is the metallic salt content of considerable solubility in water which controls the insulation or conductivity characteristics of such materials. Washing with water improves the insulation properties decidedly and improvement can be obtained by replacing the soluble salts with more insoluble salts by chemical reaction.

Work continues in an increased amount on the subject of polar molecules in dielectrics. This subject, originally considered of no practical value, is now being studied for viscous liquids and even solids, with very important results. Development of polar molecules in insulating oils gives a measure of deterioration. The work of W. N. Stoops points out the very definite correlation and the fact that the measure of the polar characteristics under accelerated test may furnish a measure of the useful life of an oil.

Dielectric losses in highly refined insulating oils at commercial frequencies and operating temperatures have been shown to result from conduction, but at high frequencies and low temperatures the major loss may be accounted for by the orientation of polar molecules. (H. H. Race, *Physical Review*, Vol. 37, p. 430–436, Feb. 1931.)

At Johns Hopkins University and the Bell Telephone Laboratories further studies on abietic acid and rosin have been made as to the part played by dipoles in the s.i.c. and loss characteristics of material over ranges of temperature and frequency. This type of work, directed toward an understanding of the mechanism of the dielectric in detail, is most important. It is interesting to note that both sets of data can be explained by the generalized theories of Schweidler and Wagner, which consider the dielectric mass as a whole, or by the dipole theory of Debye, which considers the microscopic structure, namely, the individual atoms, molecules, or ions as dipoles.

Studies of cable oil and cable conditions at a number of laboratories were reported last year, particularly on the effect of ion bombardment on oils. The necessity for a completely filled, solid, compact cable to prevent internal ionization is further shown. For example, it has been shown by the Detroit Edison Company that the power factor of an oil is directly correlated with the amount of hydrogen freed by ion bombardment. In the studies of the fundamental properties of paper, oil, and impregnated paper at Johns Hopkins University, it was found that with high grade oil the larger portion of the dielectric loss was attributable to the paper. Further, it has been shown by the Commonwealth Edison Company that tackiness of adhesion of the compound is correlated with long life of cables.

J. A. Scott of the General Electric Company has shown that oil pressures of several atmospheres applied to impregnated paper insulated cable give a decided increase in the life of the cable as measured by an endurance test.

The increased use of the oil filled type of cable and the growing use of oil for filling joints in ordinary impregnated paper insulated cable have greatly increased the importance of the integrity of the lead sheath. Several research projects dealing with lead are in progress. Work at the University of Illinois has shown that the creep of lead and several common lead alloys occurs at stresses below 200 lb. per square inch; that is, at stresses which may occur in cable sheaths during normal operation.

Researches on transmission cables show a tendency to depend on accelerated aging tests as a measure of the life quality. Both utilities and cable manufacturers are conducting researches on long lengths of impregnated paper insulated cable to duplicate in a short time what takes place over a period of years in service. The present indications are that, by subjecting the cable to about 2.5 times normal voltage, and at the same time superposing loading cycles resulting in a maximum temperature somewhat above the limiting temperature for the cable, and by making measurements of power factor and ionization factor at suitable intervals throughout a test continuing a week or two, it is possible to predict the effect of many years of normal service on the stability of insulation.

Considerable interest is taking place as to the influence of pressure on a cable and its relationship to the migration of the oil in the cable as it goes through its temperature cycle.

The Detroit Edison Research Department reports that chemical reactions of organic compounds in electrical discharges are being studied as a part of a program of investigation of the deterioration of oil-impregnated paper insulation of high-tension cables. The results of an experimental survey covering 57

different hydrocarbons has been published (*Jour. Phys. Chem.*, Vol. 35, 3649 (1931)).

In the field of insulation, J. B. Whitehead summarizes the accomplishments for the year as follows:

This research has been characterized by a definite extension of our knowledge of the behavior of insulating liquids and its causes. This is a result largely of the development of amplifier and oscillograph methods for measuring short-time behavior of liquids when used for the impregnation of paper with the result that a much closer insight is now possible as to the origin of the properties of high-voltage impregnated paper insulation. A continuation of the accelerated life studies on laboratory samples of impregnated paper is clearing up the uncertainties heretofore existing as to the relative importance of residual air and moisture in impregnated paper. In connection with these researches, an important method of analysis of the results of a-c. measurements has been developed and its limitations explored.

Circuit Interruption

Vacuum relays developed in Germany have been introduced into this country which make use of the flexibility of glass to transmit sufficient motion to operate contacts. This is possible because of the very small contact separation necessary in a vacuum.

Slepian and Strom in an Institute paper (Electrical Engineering, Dec. 1931) have given a valuable analysis of the factors which govern arc extinction in low-voltage network cables. It is shown that the gas blast, as the result of the action of the arc on cable insulating materials, is largely responsible for the clearing of faults. Data are given on the extinguishing characteristics of various types of chemical compounds.

By intensive research, the possibilities of boric acid in connection with circuit interrupting devices have been developed to a point where commercial applications are in sight. The production of water vapor from the boric acid by the action of the arc causes a powerful deionizing action. The water vapor may be condensed, thus making possible a very efficient enclosed fuse for high interrupting capacities.

Miscellaneous

H. B. Dwight has given a very useful analysis of the proximity effects in cable sheaths (A.I.E.E. Transactions for September). This is supplementary to the formulas published by him some years ago in the *Electric Journal*.

In the same issue of the Transactions there is a group of papers on the measurement and analysis of noise in electrical machinery which in some aspects represents contribution of new knowledge as the direct result of careful research. The science of acoustics is becoming an important phase of electrical engineering. Since the world has become noise conscious the elimination of unnecessary noises will be only a matter of time. Some of the new portable noise analyzers which have been placed on the market this last year make the measurement of the magnitude and the analysis of noises much easier.

By studies at the Westinghouse Laboratories, of car and train models in wind tunnels, fundamental data have been obtained on the advantages of streamlining. These results will be of great value in reducing power and making possible high-speed land transportation.

R. M. Baker has discovered that the presence of small quantities of mercury vapor in a non-oxidizing atmosphere very greatly reduces the contact resistance for certain types of brushes and slip rings. This may be of some commercial value, especially where it is wished to use very high current densities. (*Elec. Journal*, February 1932.)

The development of the helical groove on slip rings and commutators by G. M. Little promises to be of considerable value in connection with the problem of current collection and commutation. Field tests have shown decided improvements in brush wear, sparking and distribution of current between parallel brushes. (Electrical Engineering, June 1931, p. 427.)

Researches on the conditions desirable for the greatest human comfort, namely, the effect of humidity, wall temperature, air flow, and ionic condition of the air, etc., have been very active during the past year. Also the usefulness of reversed refrigeration for the heating of houses and buildings is being tried out commercially in several installations. Air conditioning is apparently to become soon a very considerable industry of great importance to the electrical interests.

Very sensitive research measurements have shown that all metals flow to some extent at high temperatures and that this flow can be reduced by using proper heat treatment of certain alloys. Such studies are used as a basis for new mechanical design of high temperature steam and electrical turbines so that proper clearance will be maintained throughout long life. (Paper presented by F. P. Coffin and T. H. Swisher at the National Applied Mechanics Meeting of the American Society of Mechanical Engineers, June 15, 1931.)

In the field of radio, Bruce's work on directive short wave antennas is of importance.

There are two recent developments in piezo-electricity worthy of note. Thin plates of tourmalin have, within recent months, shown themselves to be excellent piezo-oscillators, particularly for very short waves down to about two meters wavelength. An interesting circumstance in this connection is that, although tourmalin was one of the very first piezo-electric crystals to be studied, nevertheless the practical applications are of very recent date. Another recent application of piezo-electric crystals is their use in filter circuits of very high selectivity.

The researches on the fundamental electrical units which have been under way at the Bureau of Standards for several years have reached a stage such that preliminary values can be given, subject to some minor corrections. The results confirm earlier determinations in showing that the international ohm is 5 parts in 10,000 larger than it should be, while the

ampere has very nearly the correct value as determined by measurement of mechanical forces between coils. Comparisons of fundamental standards in recent years have shown differences between the standards of different countries large enough to be troublesome in precise scientific work. Direct comparisons between silver voltameters of the Bureau of Standards, the British National Physical Laboratory and the German Physikalisch-Technische Reichsanstalt were made during the year at Berlin; these proved that existing discrepancies arose in large part from changes in the German standard cells. Several years ago the International Committee on Weights and Measures decided that eventually the electrical units should be based upon absolute (mechanical) measurements rather than upon standards arbitrarily defined. The International Committee meets in 1933, and it is hoped that definite plans can then be approved for introducing electrical units on the new basis, assuring international uniformity of values, and removing the discrepancy between electrical and mechanical units.

Electrical Machinery

ANNUAL REPORT OF THE COMMITTEE ON ELECTRICAL MACHINERY*

Activities of the Committee

The committee during the year has reviewed approximately 50 papers, of which 24 have actually been accepted and published. Work on the preparation of test codes has been carried on during the year, and the Transformer Test Code was published in preliminary form in October. Favorable comments have been received on this, and work on the test codes for induction machines, synchronous machines, and d-c. machines is now approaching completion.

While direct responsibility of the machinery committee for standards, except for transformers, has now been transferred to the Sectional Committee of the A.S.A., the machinery committee has participated indirectly in the revision of the rotating machinery standards, and in particular has sponsored proposals to determine accurate efficiencies of induction and direct-current motors. Mr. C. J. Koch's paper on *Measurement of Stray Load Loss in Polyphase Induction Motors*, presented at the Providence Meeting of the Institute in May 1932, is an important contribution in this field.

The transformer subcommittee has been very active in revising the Transformer Standards No. 13, and it is now undertaking the very important task of standardizing impulse voltage tests.

Revisions in the standards for constant-current transformers and in the Standards Report on Capacitors have also been prepared.

Synchronous Machines

One of the 200,000-kva., 0.8-power factor, 1800-r.p.m. steam turbine-driven alternators (GE)[1] in the Brooklyn Edison Company's plant has been operated successfully at its rated kilowatt output, and the second unit is being installed. A 121,000-kva., 18,000-volt, 1,800-r.p.m. (AC) unit was placed in operation at Waukegan, and a 147,000-kva., 22,000-volt unit (AC) for the State Line Station is under construction. A 25,000-kva., 13,800-volt, 3,600-r.p.m. machine (W) was shipped to the Public Service Electric and Gas Company and is the largest unit yet undertaken at this speed. A 99,000-kva., 13,800-volt, 1,800-r.p.m. generator (W) is under construction for this company and is the largest unit so far built with internal fans.

Five vertical-shaft waterwheel-driven alternators rated at 48,500 kva., 13,800 volts, 25 cycles, 750 r.p.m. (CGE) are under construction for the Abitibi Cangon Development near James Bay.

A 1,250-kva., 960-cycle, single-phase generator (GE); a 1,250-kva., 1,000-cycle, single-phase generator (GE); and a 3,000-kva., 420-cycle, single-phase generator (GE) represent increases in capacity over high-frequency machines of this type built before the year 1931.

A 75,000-kva., 12,600-volt, 514-r.p.m., synchronous condenser (W) is under construction for the Commonwealth Edison Company. This is an increase of fifty per cent over the previous largest synchronous condenser.

During the year there has been considerable activity in the development of designs to improve the starting performance of industrial synchronous motors, particularly as to higher torque per kva. inrush. Several motors of 200 to 600 hp. at 300 to 900 r.p.m. have been built with a starting torque efficiency (per cent starting torque over per cent kva. inrush or unity power factor base) of the order of 55 per cent.

* COMMITTEE ON ELECTRICAL MACHINERY:
P. L. Alger, Chairman, General Electric Co., Schenectady, N. Y.,
B. L. Barns, E. S. Bundy, H. E. Edgerton, J. E. Goodale, T. T. Hambleton, A. L. Harding, C. F. Harding, E. W. Henderson, S. L. Henderson, L. F. Hickernell, J. Allen Johnson, J. J. Linebaugh, H. C. Louis, A. M. MacCutcheon, O. K. Marti, V. M. Montsinger, R. W. Owens, R. H. Park, E. B. Paxton, H. V Putnam, K. A. Reed, A. M. Rossman, O. E. Shirley, R. G. Warner, C. A. M. Weber, R. B. Williamson.

[1] Manufacturer Designation:
AC—Allis-Chalmers Manufacturing Company
BB—American Brown Boveri Company
CGE—Canadian General Electric Company
CW—Canadian Westinghouse Co., Ltd.
ED—Electric Dynamic Company
EM—Electric Machinery Manufacturing Company
GE—General Electric Company
W—Westinghouse Electric & Manufacturing Company

Two motors for pulp grinder drive (EM) will use stator windings in four parallels, and these motors will be started by applying successively the parallel circuits all on the reduced voltage of the auto-transformer. These suitably timed increments will reduce the kva. inrush to a minimum.

The twelve 5,500-hp. motors (GE) for the U. S. Mail S.S. Company have been completed, and two ships with two motors each are in service.

The S.S. *President Hoover* (GE) and the S.S. *President Coolidge* (W) each with two 13,250-hp. motors were placed in service during the year.

Two 30,000-kilowatt frequency changers (GE) with generators rated 42,860 kva., 0.70 power factor, single-phase, 25 cycles, and motors rated 36,000 kva., 0.9 power factor, three-phase, 60 cycles, and operating at 300 r.p.m. are being installed at the Richmond Station of the Philadelphia Electric to supply power to the Pennsylvania Railroad electrification. These sets have twice the capacity of single-phase sets previously built. The generators are equivalent mechanically to 61,000-kva., three-phase machines. The frequency changers are designed for outdoor operation in steel enclosing housings.

Induction Machines

There has been considerable activity during the last year in induction machines. The demand for squirrel-cage motors for rapid and oft-repeated reversing duty, of a nature heretofore confined to d-c. mill type motors, has led to the development of special motors with low inertia rotors and liberal radiating surfaces. This demand came chiefly from the steel mill industry and concerned motors for use on furnace conveyers of the "stroke" type and motors for newly developed automatic sheet handling apparatus as used for hot finishing mills. The simple squirrel-cage motor, while it has some disadvantages as regards disposition of loss, nevertheless offers many advantages for this type of service, *e. g.*, a low-inertia, sturdy, dependable, simple, rotating element, simplified control; faster-operating control; lower-cost motor and lower-cost control. The opening up of this field to squirrel-cage motors will undoubtedly add to the wider application of this type of motor.

The use of totally enclosed fan-cooled motors has increased enormously. One company reports that over half of its induction motor production for last year was of the fan-cooled type. This type of motor is available in mounting dimensions the same as those for open motors of equal rating up to fairly large sizes, and has been well received by the trade where open type motors were subject to aggravated dirt conditions.

Selsyn motors as mediums of control formed a successful means of maintaining levels on both ends of a lift bridge on the Missouri, Kansas, Texas Ry. Other novel applications of this type of motor as a control or as an indicator are under way.

Induction frequency converters of the commutator type have, during the year, been built for use at frequencies as low as $2^1/_2$ cycles. Machines of this type with outputs at ten cycles have been supplied by a large manufacturer to increase the range of his slip-ring frequency converters. These latter, driven by a d-c. adjustable-speed motor, have a normal range of 120 to 180 cycles. By supplying 10 cycles to these converters at approximately $^1/_6$ normal voltage, the frequency range of these converters became 70 to 130 cycles, and a range of 70 to 180 cycles was made possible. These latter frequencies were used to supply small high-speed squirrel-cage motors and give them adjustable-speed characteristics for improvement in manufactured product.

Direct-Current Machines

A triple unit motor has been built (ED) for ship propulsion. One auxiliary and two main motors are placed in line with their armatures on one shaft. The auxiliary motor is designed for low cruising speed with higher efficiency than could be obtained in the main motors at low speed.

Two 2,500-hp., 282/708-r.p.m., constant-torque, induction motors have been built (AC) for driving reciprocating, 1,500-lb. per sq. in., boiler feed pumps. The Rossman system of varying speed is used. This is the first case where the d-c. armature has been mounted directly on the rotatable induction motor primary.

A 12,500-hp., 44-inch, slabbing mill drive (W) has been placed in operation. Each main roll is separately driven, without pinions, by a 5,000-hp. double-unit motor; the edging rolls by a 2,500-hp. single motor. Power is supplied by a 10,500-kw., 700-volt, d-c. set composed of one induction motor, 180,000-lb. flywheel, and three 3,500-kw. generators.

A roll grinder has been equipped (W) with nine d-c. motors for controlling separately every motion and adjustment.

Transformers

Manufacturers have given increased attention to the design of both power and distribution transformers to better withstand lightning surges and to developing methods of impulse testing to indicate weakness in transformer insulation to such surges.

Several large shell-type surge-proof power transformers (W) of the new type were built, among them units of 42,000 kva., 220 kv. which were subjected to unusually severe impulse tests, 4,500-kva. units for the Pennsylvania Railroad and a 70,000-kva. unit for the United Electric Light and Power Company, which is thought to be the largest of the self-cooled type in this country.

Self-contained features for protection against lightning independently of transformer connections or grounding practise, and for prevention of outages, were accomplished by incorporating high-voltage deion gaps and coordinated low-voltage bushings in standard distribution transformers (W).

Cover-roof type bushings are a feature of a new line of distribution transformers (AC) intended particularly for service on rural lines.

Two transformers (GE) of new design were fur-

Table I. Mercury Arc Rectifier Units Placed in Operation During 1931 or on Order December 31, 1931

Purchaser	No. of Sets	D-c. Volts	Kilowatts per Set	Total Kilowatts	Type of Control	Service	Placed in Service	Manufacturer
Amer. Gas & Elec. Co., New York	2	610	500	1,000	Automatic	Railway	1931	BB
Boston Elevated Railway	2	600	3,000	6,000	Automatic Remote Control	Railway	1931	GE
Cleveland Railway Company	x1	600	500	500	Semi-Automatic	Railway	1931	W
Clinton, Davenport & Muscatine Rwy	1*	700	500	500*	Automatic	Railway	1931	BB
Commonwealth Edison Co.	3	625	3,125	9,375	Manual	Railway	1931	BB
Commonwealth Edison Co.	1	625	2,080	2,080	Automatic	Railway	1931	BB
Commonwealth Edison Co.	1	625	3,125	3,125	Automatic	Railway	1931	BB
Commonwealth Edison Co.	1	625	3,125	3,125	Manual	Railway	1931	GE
Commonwealth Edison Co.	1	625	3,125	3,125	Manual	Railway	1931	GE
Commonwealth Edison Co.	1	625	3,125	3,125	Manual	Railway	1931	GE
Consol. Mining & Smelting Co. of Can.	1	650	6,500	6,500	Manual	Electrolytic	1931	GE
Consol. Mining & Smelting Co. of Can.	2	650	6,500	13,000	Manual	Electrolytic	1931	BB
Detroit, City of	1	600	2,000	2,000	Automatic	Railway	1931	GE
I. G. Farbenindustrie for Standard Oil Co. of Louisiana	°1	3,500/9,600	2,200	2,200	Manual	Electrochemical	Being erected	BB
Illinois Power & Light Company	1	650	540	540	Automatic	Railway	1931	W
Indiana Railroad Company	2	625	850	1,700	Manual	Railway	1931	BB
Long Island Railroad Company	x1	650	3,000	3,000	Automatic Remote Control	Railway	1931	W
Long Island Railroad Company	5	650	3,000	15,000	Automatic	Railway	1931	BB
Long Island Railroad Company	4	650	3,000	12,000	Automatic	Railway	On order	AC
Los Angeles Railway Corporation	2	600	1,500	3,000	Automatic Remote Control	Railway	1931	GE
Louisville Gas & Electric Co.	2	600	1,000	2,000	Automatic	Railway	1931	GE
Montreal Tramways Company	2	600	1,500	3,000	Automatic Remote Control	Railway	1931	GE
Mason City & Clear Lake Railway	1*	650	500	500*	Automatic	Railway	1931	BB
N. Y. Board of Transportation	10	625	3,000	30,000	Automatic Remote Control	Subway	1931	GE
N. Y. Board of Transportation	13	625	3,000	39,000	Automatic Remote Control	Subway	Being erected	GE
N. Y. Board of Transportation	15	625	3,000	45,000	Automatic Remote Control	Subway	On order	GE
N. Y. Board of Transportation	13	625	3,000	39,000	Automatic Remote Control	Subway	On order	GE
N. Y. Central R.R. Company	1	666	3,000	3,000	Automatic Remote Control	R.R. Electrif'n	1931	GE
Northern Indiana Pub. Service Co.	1	1,500	3,000	3,000	Automatic	Railway	1931	BB
Paris Orleans Rwy.—France	1	1,500	1,500	1,500	Automatic	R.R. Electrif'n	1931	GE
Philadelphia, City of	2	630	3,150	6,300	Manual	Railway	On order	AC
Piedmont & Northern Railway	1	1,500	750	750	Auromatic	R.R. Electrif'n	1931	W
Quebec Power Company	1	550	1,200	1,200	Automatic	Railway	1931	BB
Regina, City of	1	575	1,200	1,200	Manual	Railway	1931	BB
Sun Life Assurance Co. of Canada	2	250	400	800	Manual	Power	1931	BB
Trenton Transit Company	3	600	1,400	4,200	Manual	Railway	1931	BB

* In addition, one spare rectifier (without transformer) was supplied.
x Temporary installation.
° Also reported 1930.

Totals*	1931		1930	
	No. of Sets	Kilowatts	No. of Sets	Kilowatts
Placed in service	57	127,845	33	75,225
Being installed	14	41,200	26	71,400
On order	34	102,300	29	79,275
Grand total for year	105	271,345	88	225,900
Total number units in service, Dec. 31st	180	305,379	123	177,534

* Spare rectifier tanks without transformers not included.

nished to operate an X-ray tube for cancer research in the California Institute of Technology. Each unit is rated 0.03 ampere at 700,000 volts to ground continuously, and operates in series with mid-point grounded, giving 1,400,000 volts effective at the X-ray tube.

Magnetic oil level indicators were made available (GE and AC) for power, large distribution, and high-voltage instrument transformers. This gage has numerous advantages over a glass oil gage because it is more easily read, and more easily maintained oil tight. It has no glass to become dirty on the inside or break and allow oil to run out.

The number and capacity of load-ratio control transformers exceeded all previous records. The development of a design (GE) suitable for lower-rated circuits up to 15,000 volts, single-phase or three-phase, resulted in an economical application of load-ratio control to distribution transformer sizes. This type of equipment was applied to the new three-phase 1,500-kva. transformers for high-voltage networks. A new line of standard tap changers (W) using standard parts suitable for wide range of capacities as low as 200 kva. were completed.

A new type of inertaire protection for power transformers (W) using nitrogen from a gas cylinder was perfected. A uni-directional breather (AC) for use on power transformers, which induces a natural circulation of air over the oil in the main transformer tank or expansion tank to reduce condensation and carry off condensed moisture, was developed.

Mercury-Arc Rectifiers

The use of rectifiers has continued to expand during the year as indicated by information contained in Table I.

The large number of additional 3,000-kw. 625-volt units ordered by the New York Board of Transportation is the outstanding feature of this year. Twenty-three of these rectifiers were ordered last year and 28 this year, making a total of 51 sets (GE) with a total capacity of 151,000 kw.

The three 6,500-kw., 650-volt electrolytic rectifiers listed in this and last year's report were placed in service during the year.

A 3,000-kw., 650-volt sectional rectifier (W), consisting of four 750-kw. separate rectifiers arranged in a compact unit, was developed and placed in service.

The first complete portable mercury-arc rectifier substation, consisting of a 540-kw., 650-volt (W) rectifier with transformer and control, cooling system, car, etc., was placed in service by the Illinois Power & Light Company.

Protective Devices

ANNUAL REPORT OF THE COMMITTEE ON PROTECTIVE DEVICES*

THE work of the Committee on Protective Devices during the past year was handled largely through subcommittees as has been the practise for several years. These subcommittees are listed below together with their chairmen:

Relays	O. C. Traver
Oil Circuit Breakers, Switches, and Fuses	T. G. LeClair[1]
Lightning Arresters	H. K. Sels
Fault Current Limiting Devices	R. T. Henry
Interconnections[2]	F. C. Hanker

GENERAL

The committee continued its activities in following the preparation of standards, and review of research and development, although the main activity during the year was fostering the preparation and presentation of papers before the Institute.

While the technical achievement during the year is very satisfactory in view of the general business conditions, these conditions of course had a depressing effect on research and developmental activities. Progress in this respect consisted largely of refinements and extensions of fundamentals previously established.

Difficulty in securing agreement relative to certain matters concerning the standards for fuses and the revised standards for disconnecting, horn-gap and knife switches has prevented completing these standards. Plans have been made for a course of action which it is believed will permit of putting these standards into report form. Every effort is being made to place these standards in such shape that complete agreement may be secured which will permit their adoption as Institute Standards.

RELAYS

Report of Subcommittee

The development of high-speed relays continued, resulting in marked improvements to primary power-system relays generally, and in new developments in the a-c. railway and secondary distribution network system fields.

One of the manufacturers has developed so-called straight-line relays, particularly for application on 4,000-volt networks which are capable of discriminating and operating on very small differences in current, although these currents may be quite heavy.

An important advance during the year was the redesign of all types of relays by at least one manufacturer in order to accommodate the relays in a new universal case, with standard stud arrangement, which is being used to a large extent for front of panel switchboard devices.

A high-speed current differential relay for transformer protection having an operating speed of 0.004 second has been developed.

Numerous refinements in mechanical details contributing to the reliability and accuracy of relays of all types have been carried forward.

Completed developments in coupling and protective equipment for all carrier-current applications include cable-type coupling-capacitor assemblies for all voltages from 115 to 230 kv., inclusive.

In order to secure a consensus of present day practise in regard to protection of apparatus of all classes, a questionnaire on this subject has been sent to a number of engineers, and a number of replies has already been received.

An important advance in relay application during the past year has been the wide increase in the use of the method of symmetrical components for determination of not only the fault current but also the voltage and current at the relay location, particularly for distance relay applications.

The following papers appearing under the auspices of the committee have been presented before the Institute:

A New High-Speed Distance Relay, S. L. Goldsborough and W. A. Lewis, Westinghouse Electric & Manufacturing Co.

Application of High-Speed Relays, G. W. Gerrell, Union Electric Light & Power Co.

A New High-Speed Distance Relay, A. R. Van C. Warrington, General Electric Co.

Relay Operation From Bushing Potential Devices, P. O. Langguth, Westinghouse Electric & Manufacturing Co., and V. B. Jones.

Operation of Relays From Carrier-Current Coupling Capacitors and Capacitance Transformer Bushings, J. E. Clem and R. E. Cordray, General Electric Co.

Effect of Wave Form on Operation of Induction Relays, P. H. Robinson, Houston Lighting & Power Co.

A Telegraphic Pilot-Wire Relay System, C. H. Frier, Oklahoma Gas & Electric Co.

OIL CIRCUIT BREAKERS, SWITCHES, AND FUSES

Report of Subcommittee

Intense interest has been shown during the year in the fundamental theories underlying the various circuit breaker developments of the last few years. These discussions have resulted in clarifying concep-

* COMMITTEE ON PROTECTIVE DEVICES:

Raymond Bailey, Chairman,
L. F. Hickernell, Vice-chairman,

H. W. Collins,	T. G. LeClair	H. P. Sleeper,
A. W. Copley,	J. B. MacNeill,	L. G. Smith,
W. S. Edsall,	J. P. McKearin,	E. R. Stauffacher
L. E. Frost,	H. A. McLaughlin,	H. R. Summerhayes,
S. L. Goldsborough,	D. M. Petty,	O. C. Traver,
R. T. Henry,	H. J. Scholz,	E. M. Wood,
E. A. Hester,	H. K. Sels,	H. B. Wood.

[1] Mr. LeClair was appointed chairman of the subcommittee on oil circuit breakers, switches, and fuses on January 4, 1932, when Mr. Hickernell resigned as chairman of this subcommittee.

[2] The interconnections subcommittee is a joint subcommittee having representation from the following committees: Protective Devices, Power Generation, Transmission and Distribution, Electric Machinery.

tions of the theories on which these new types of breakers operate and have laid ground work for further development in the future. The amount of fundamental development which this intensive scrutiny reveals will, if supported by satisfactory performance records, do much to increase the confidence of the user in the ability of oil circuit breakers to perform adequately.

The metal-clad switchgear has been improved in a number of details and the development has been extended to interrupting ratings of 500,000 kva. at 15 kv. for indoor breakers and to 1,500,000 kva. at 132 kv. for outdoor breakers.

The oil-blast and deion grid principles of breaker construction were extended to quite high ratings, and both types have appeared in the metal-clad construction. Elaborate tests on a 1,500-ampere 15-kv. high-speed deion circuit breaker were performed for a railway application. Seventy-two short circuits ranging from 2,720 amperes to 50,500 amperes were thrown on the breaker in about five hours time. Some of these short circuits lasted only 0.024 second and the duration of the longer ones was 0.04 second. A series of fifty tests at current values from 11,000 to 49,000 amperes was run on impulse type of oil-blast breaker of a corresponding rating. This breaker clears the circuit in 0.04 second or less over the full current range.

Developments in air circuit breakers include extension of current ratings and improvements in operating speed.

The fuse manufacturers have been active in the development of improved type fuses, which are more economical.

There is a fairly widespread feeling among operating engineers in particular that some improvement could be made on the basis of rating of oil circuit breakers.

The following papers appeared under the auspices of the committee and have been presented before the Institute:

The Theory of Oil-Blast Circuit Breakers, D. C. Prince, General Electric Co.

The Practical Application of the Oil-Blast Principle of Circuit Interruption, R. M. Spurck, General Electric Co.

Recent Developments in Arc Rupturing Devices, R. C. Van Sickle and W. M. Leeds, Westinghouse Electric & Manufacturing Co.

The Extinction of Alternating Current Arcs in Turbulent Gases, T. E. Browne, Jr., Westinghouse Electric & Manufacturing Co.

Application of Primary Distribution Fuses, F. E. Sanford, Union Gas & Electric Company.

The Expulsion Fuse, J. Slepian and C. L. Denault, Westinghouse Electric & Manufacturing Co.

Fuse Cut-Outs—Their Design and Application for A-C. Distribution Circuits, E. G. Newton, General Electric Co.

The Boric Acid Fuse, A. P. Strom and H. L. Rawlins, Westinghouse Electric & Manufacturing Co.

Fault Current Limiting Devices

Report of Subcommittee

The committee is not aware of any developments relating to fault current limiting devices of sufficient importance to warrant including in this report. Operating experience with such devices apparently continues to be quite satisfactory, and the need for further development is therefore not particularly urgent.

Lightning Arresters

Report of Subcommittee

As in other lines, the developments on lightning arresters consist principally of extensions of recently developed, fundamental theories to a greater variety of forms of station and line type arresters; also, a marked improvement has been made in the mechanical design and construction of lightning arresters which will improve the maintenance of their electrical characteristics.

Studies of lightning and the effects of lightning on power systems were continued during the year with considerable improvement in the technic of fault location. Newly developed lightning current meters and special low resistors were used to measure the current in the lightning stroke.

Continued field investigations using portable surge generators and cathode ray oscillographs, were made in conjunction with study of applications of lightning arresters to distribution transformer installations and associated line construction.

Considerable experimental work concerning grounds and ground connections resulted in making available information which may be used to improve the effectiveness of lightning arrester applications.

New protective devices have been developed, arranged for installation inside of the distribution transformer. This development marks a new phase in the problem of protection of transformers against the effects of lightning and should result in very much improved operating experience.

A report is in preparation jointly with the N.E.L.A. Subject Committee on Lightning Arresters, outlining the prevailing practise on the installation, operation, and experience of various types of lightning arresters by a number of the larger operating companies. This information should be valuable in observing the present trend of operating practise on transmission and distribution systems relative to arrester installation, operation, and performance as affecting suitable standards, and also whether tests and equipment should be developed to determine the operating condition of arresters in service.

Lightning arrester manufacturers have contributed largely to the development of more powerful testing equipment and more accurate recording apparatus which has been used to carry out the proposed tests outlined in the Report on Standards for Lightning Arresters and has effectively demonstrated the value

of these tests to determine the characteristics of lightning arresters.

The report on Standards for Lightning Arresters continues in its tentative form and it will probably not be feasible to revise this report until work now in progress on the characteristics and coordination of system insulation with respect to lightning has progressed further.

Interconnections

Report of Joint Subcommittee

The Joint Subcommittee on Interconnections includes representatives of the Protective Devices, Power Generation, Transmission and Distribution, and the Electric Machinery Committees.

At the Winter Convention 1932 the session under the auspices of the subcommittee included two subjects of particular interest to the Protective Devices Committee, namely, the "Report of the Subject Committee on Definitions of Terms Used in Power System Studies" and the papers presenting revised decrement curves.

The activity of various engineering groups in studies of interconnection has built up a terminology for which there has been no official recognition. A Subject Committee has been at work on these definitions for some time and presented a report that will be used as the basis for the consideration of such definitions by the responsible standardizing bodies. A large number of these definitions is related to subjects of interest to the Protective Devices Committee.

The papers on decrement curves and short circuit calculations are:

I—Standard Decrement Curves, W. C. Hahn, General Electric Co., and C. F. Wagner, Westinghouse Electric & Manufacturing Co.

II—Calculation of Short Circuits on Power Systems, C. F. Wagner, Westinghouse Electric & Manufacturing Co., and S. H. Wright, Buffalo, Niagara & Eastern Power Corporation.

III—Decrement Curves for Specific Systems, W. C. Hahn, General Electric Co.

During 1918, Messrs. Burnham, Hewlitt, and Mahoney discussed decrement curves for relay and circuit breaker applications before the Institute. The group of papers presented at the last Winter Convention brings the subject up to date, utilizing the further knowledge of machine characteristics accumulated in the intervening period.

Instruments and Measurements

ANNUAL REPORT OF COMMITTEE ON INSTRUMENTS AND MEASUREMENTS*

THE Committee on Instruments and Measurements during the year 1931–32 has had an active membership of 23 members. At the meeting held in October 15 members were in attendance, and at the meeting held in January 13 members attended. Considering the geographical distribution of the membership, this attendance is exceptionally good.

The work has been organized through subcommittees to take care of the following subjects:

1. Recording instruments
2. Telemetering
3. Definitions of instruments and testing
4. Instrument transformers
5. Indicating instruments
6. Temperature measurements
7. High-frequency measurements

Subcommittee on Recording Instruments

This subcommittee has been engaged for several years on the development of standards for recording instruments. During the year its work was completed and a draft of the proposed standards was approved by the Instruments and Measurements Committee. These have been forwarded to the Secretary of the Standards Committee for adoption and publication. This subcommittee has been under the chairmanship of Mr. Kinnard and is to be complimented on the completion of a task which involved such a large amount of painstaking work.

Subcommittee on Telemetering

This subcommittee has concluded its work on standard definitions which have been approved by the Instruments and Measurements Committee. These have been submitted to the Secretary of the Standards Committee.

In addition to its work of following developments in this field, it has undertaken to cooperate with a subcommittee of the Automatic Stations Committee in the preparation of a report on telemetering and supervisory control systems and related communication systems. This report is a very comprehensive survey of all the known telemetering systems, which have been critically analyzed so as to provide detailed information in regard to the limitations and operating characteristics of each. It is hoped to have this report for the Summer Convention. Mr. E. D. Doyle is chairman of this subcommittee.

* COMMITTEE ON INSTRUMENTS AND MEASUREMENTS:

E. J. Rutan, Chairman,

H. S. Baker,	Marion Eppley,	F. A. Laws,
R. D. Bean,	J. B. Gibbs,	E. S. Lee,
O. J. Bliss,	W. N. Goodwin, Jr.,	J. B. Lunsford,
P. A. Borden,	I. F. Kinnard,	Paul MacGahan,
H. B. Brooks,	O. A. Knopp,	R. T. Pierce,
A. L. Cook,	A. E. Knowlton,	W. J. Shackelton,
E. D. Doyle,	H. C. Koenig,	H. L. Thomson,
W. W. Eberhard,	W. B. Kouwenhoven,	H. M. Turner.

Subcommittee on Definitions of Instruments and Testing

This subcommittee is an outgrowth of the cooperation of the Instruments and Measurements Committee with the Sectional Committee of the American Standards Association which is preparing definitions on instruments and testing. Mr. E. S. Lee as chairman of this subcommittee has been assisted by the chairmen of the Recording Instruments, Telemetering, Instrument Transformers, and Indicating Instruments subcommittees as well as all of the members of the Instruments and Measurements Committee. Many valuable suggestions and considerable work has been done in the criticism, correction, and rearrangement of several of the drafts of definitions submitted to this subcommittee. Joint meetings were arranged with the members of the Sectional Committee and, as a result, an acceptable draft of these definitions has been completed.

Subcommittee on Instrument Transformers

The Subcommittee on Instrument Transformers has been active for the past two years in the revision of standards No. 14 and has about completed its work and is preparing to submit a final draft of these standards to the members of the Instruments and Measurements Committee. Mr. J. B. Gibbs is chairman of this subcommittee.

Subcommittee on Indicating Instruments

Indicating instruments standards No. 23 which have been available to the industry since 1927 have been under consideration for revision during the past year. Based on considerable progress in the art since the standards were issued and the experience of the Instruments and Measurements Committee, many desirable changes will be made and new data incorporated in these standards. An early report from this subcommittee is expected which, upon approval by the Instruments and Measurements Committee, will be forwarded to the Standards Committee. Mr. H. C. Koenig is chairman of this subcommittee.

Subcommittee on Temperature Measurements

This subcommittee, which is under the chairmanship of Mr. H. C. Koenig, has been working on the preparation of a standard code for temperature measurements. The scope of this work is to cover all the requirements of temperature measurements as specified in the various standards of the Institute. It is expected, when completed, a very comprehensive procedure will be available for uniform measurements of temperature.

Subcommittee on High-Frequency Measurements

This subcommittee has been active under the chairmanship of Prof. H. M. Turner. Arrangements were made to cooperate with a committee appointed by the Standards Committee to draft definitions and standards for sound measurements. The subcommittee is also making a study of vacuum tube voltmeters and will prepare a report on this subject during the coming year.

Institute Sessions and Papers

In addition to the Committee work through its subcommittees on definite subjects, arrangements were made for the promotion of a session at the Mid-Winter Convention. Six papers were presented and are listed below:

1. *High Voltage Bridge for Measurements of Cable with Grounded Sheaths*, C. L. Dawes and A. F. Daniel.
2. *A High Sensitivity Power Factor Bridge*, W. B. Kouwenhoven and Alfredò Banos, Jr.
3. *Capacitance and Power Factor Measurement by the Capacitance Bridge*, R. P. Siskind.
4. *An Automatic Oscillograph*, C. M. Hathaway and R. C. Buell.
5. *The Photoelectric Recorder*, C. W. La Pierre.
6. *Aging and Elastic Hysteresis in Instrument Springs*, P. MacGahan and R. W. Carson.

In addition to the papers presented at the session, the following papers were reviewed by the various members of the Instruments and Measurements Committee and commented upon:

1. *The Metering of Symmetrical Components*, G. R. Shuck.
2. *Electrical Measurements of Sound Absorption*, A. L. Albert and W. R. Bullis.
3. *Electrical Solutions of Problems of Regular Scheduled Flight*, C. F. Green.
4. *The Photoelectric Recorder*, C. W. La Pierre.
5. *A Standard of Low Power Factor*, W. B. Kouwenhoven.
6. *Electrical Measurements in the Gas Industry*, E. X. Schmidt.
7. *A Special Application of the Potentiometer Principle*, J. L. Watson and R. C. Gleeson.
8. *A Bridge for Precision Power Factor Measurements on Small Oil Samples*, J. C. Balsbaugh and P. H. Moon.
9. *Skin Effect in Rectangular Conductors*, H. C. Forbes and L. J. Gorman.

Conclusion

The Chairman wishes to acknowledge at the completion of his two years of office the hearty cooperation of all of the members of the Instruments and Measurements Committee. The work of the vice-chairman, secretary, and chairmen of the subcommittees was of especial importance in the successful completion of many of the projects which we had before us. From several years contact with this committee as a member and as chairman, the writer has been very much impressed by the interest displayed, and feels highly confident concerning the continued activity in this field of the electrical engineering art as sponsored by this committee.

Transportation

ANNUAL REPORT OF THE COMMITTEE ON TRANSPORTATION*

Railroad Electrification

THE Reading Company began operation on July 26, 1931, of the first portion of its electrified suburban service running out of Philadelphia. Multiple-unit cars are now operated over 64.6 miles of route embracing 156.9 track miles and the electrification of two more branches is in progress, the completion of which will bring the total electrified mileage to 86.9 route miles or 203 track miles. Single-phase, 25-cycle, alternating current is supplied by the Philadelphia Electric Company through outdoor frequency changer sets located on the railroad's property at Wayne Junction, and is distributed to the trains over a 36,000/12,000 three-wire system with 12,000 volts between the overhead contact wires and the rails, and 24,000 volts between the rails and the feeders carried on the catenary structures. Provision has been made on these structures for supporting transmission lines of higher voltage when future extensions of the electrification make it necessary. Over a part of the right-of-way steel towers are to be used jointly by the power company for high-voltage transmission and by the railroad for supporting its catenary system. All of the power switching is handled from a single supervisory control board at Wayne Junction, at which point also are located the repair shops and storage yards for the car equipment.

The Pennsylvania Railroad Company has made very considerable progress on its project for complete electrification between New York and Washington. The overhead contact system has been installed in the New York Terminal zone between Sunnyside Yards on Long Island and Manhattan Transfer in New Jersey, where d-c. third-rail locomotives have been used hitherto, and a-c. locomotives are now handling some of the trains. Construction is progressing between Manhattan Transfer and Trenton, New Jersey, the completion of which, in association with the work already done, will permit electric operation from New York as far as Wilmington. The erection of catenary structures between Wilmington and Washington has been begun. Several locomotives of the new standard designs have been placed in service. The motors on the two types of passenger locomotives (2-B-2 and 2-C-2) and the road freight locomotive (1-D-1) have interchangeable armatures, stators, and other parts, those on the passenger engines being mounted in twin frames, a pair for each driving axle, while those on the freight locomotive are mounted independently, one on each of the four driving axles. The motors all have a continuous rating of 625 hp. per armature. Standardization and interchangeability of parts have been carried out as far as possible throughout the design of these locomotives, both in the mechanical parts and in the electrical equipment. These standard motive power units may be operated in various combinations to provide the tractive effort required for different classes and weights of trains.

The New York Central Railroad has eliminated the use of steam locomotives on its "West Side" line in New York City, full operation by either electric or oil-electric locomotives having been inaugurated in June 1931. Third rails supplying direct current at 650 volts have been installed as far south as 72nd Street, but only to a very small extent in the yards between 72nd and 60th Streets. No external power supply has as yet been provided on the tracks which lead (still largely on the city streets) to the smaller yards and terminals further downtown. The locomotives which handle the switching and transfer work in this territory have oil engine-generator sets and storage batteries to provide their own power, but are also equipped to receive power from the third rail where it is available.

The New York, New Haven & Hartford Railroad has placed in operation the ten new passenger locomotives mentioned in last year's report. They weigh 403,000 lb. and have the axle arrangement 2–C+C–2 with a weight on drivers of 45,600 lb. per axle. Each of the six driving axles is connected by quill and gear to a twin motor with a continuous rating of 550 hp. These locomotives are notable for improved motor design, giving better commutation and increased tractive effort.

Oil-electric locomotives, as well as oil-electric and gasoline-electric rail motor cars, are finding an increasing number of applications. Seven such locomotives recently placed in service by the Bush Terminal Company in Brooklyn, New York, are unique in that their cabs, underframes, and trucks were fabricated entirely from structural shapes and plates, with electric welding and no riveting.

Air conditioning on passenger cars and experiments with rubber-tired rail cars are among recent developments in railroading which contain elements of interest to the electrical engineer.

Railroad Signaling

A number of additional installations of the recently developed methods of centralized traffic control was made during the past year. These, together with the completion of many new interlocking plants, automatic signals, highway crossing signals, and car retarders kept the record of progress in the installation of signaling facilities up to about 65 per cent of that in the previous year in spite of the reduction in the volume of construction in general.

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* COMMITTEE ON TRANSPORTATION:

E. L. Moreland, Chairman,

Reinier Beeuwkes,	K. T. Healy,	S. A. Spalding,
A. E. Bettis,	H. N. Latey,	N. W. Storer,
H. A. Currie,	John Murphy,	W. M. Vandersluis,
J. V. B. Duer,	Hippolyte Parodi,	R. P. Winton,
H. H. Field,	W. B. Potter,	Sidney Withington,
I. W. Fisk,	R. H. Rice,	G. I. Wright.

Urban Transportation

The New York City Board of Transportation has practically completed the equipment of the new Eighth Avenue Subway from Fulton Street to 207th Street, Manhattan, and has received 300 cars which have been tested in trial runs and are ready for the beginning of operation. Five hundred more cars have been ordered in preparation for extension of the service to other sections of the new system which are under construction in the boroughs of Brooklyn, Queens, and the Bronx. The substation equipment for these lines will include 16 converters in five substations with an aggregate capacity of 53,000 kw., and 62 mercury arc rectifiers rated at 3,000 kilowatts each, most of which will be placed in individual subterranean compartments along the subway lines.

Systematic efforts are being continued to design a type of street car which will more successfully meet the competition of the buses and the private automobiles. The tendencies are toward the use of lightweight, double-truck cars, with small wheels and low floors, equipped with small high-speed motors giving rapid acceleration and high car speeds. Control has been improved by the use of a larger number of resistance steps and also by the introduction of "variable-automatic control" in which the operation of the resistance contactors is governed by relays, but the motorman can select the rate of acceleration according to traffic or rail conditions. Braking by means of electromagnetized shoes on the car acting against the running rails is being used to some extent. Higher speed and lighter weight are the tendencies in interurban cars also, and some attention is being given to improvement in body design to reduce wind resistance.

The use of trolley buses is being extended, such vehicles having been purchased for seven cities during 1931, at the end of which year there were 225 trolley buses in operation in 14 cities in the United States.

Marine Transportation

The two largest passenger liners built in the United States, the *President Hoover* and the *President Coolidge*, were placed in operation during the past year in intercoastal and transpacific services. Each of these twin ships has two 10,000-kw. turbine-driven generators which supply the synchronous-induction propulsion motors with three-phase, alternating current at 4800 volts, and also four 500-kw. turbine-driven d-c. generators which very completely serve the auxiliary equipment on board, including steering gear, winches, capstans, air compressors, refrigerating machines, blowers, pumps of all sorts, elevators, cooking equipment, stateroom heaters, fans, etc., in addition, of course, to searchlights and general lighting. Several other smaller motor-propelled vessels with generators driven by steam turbines or oil or gasoline engines were placed in commission during the year. (See also the report of the Committee on Applications to Marine Work.)

Aerial Transportation

The U.S. Navy dirigible *Akron* carries considerable electrical equipment, including a searchlight and general lighting, cooking appliances, radio equipment, a battery charging set and other motors. The energy is supplied by two 11-kw., 115-volt d-c. generators driven by gasoline engines. The huge mooring mast, by which the dirigible is towed into and out of its hangar at Lakehurst, N. J., is propelled by two caterpillar tractors driven by 125-hp., 250-volt, d-c. motors and is steered by a third caterpillar driven by an 8-hp. motor. A 240-hp. gasoline-driven generator supplies these motors as well as floodlights and signaling apparatus on the mast and equipment for conveying water, fuel, and electricity to the dirigible.

A novel type of electric locomotive is used to tow models of sea-plane hulls or pontoons in a testing channel 2,000 ft. long, 22 ft. wide, and 12 ft. deep, recently completed at Langley Field, Va. The towing car spans the tank and is driven by four 75-hp. motors. The remarkable feature is its rapid acceleration, as it is said to reach a speed of 60 miles an hour in 9 seconds.

Important improvements were made during the year in radio equipment for communication between airplanes and the ground and for direction finding. These include automatic volume control, which relieves the pilot of the necessity of making manual adjustment of receiver amplification over a wide range of distances, and also practicable means of giving visual indication in connection with the direction finders.

Among electrical devices perfected for application to aviation may be mentioned an instrument for indicating engine cylinder temperature which is so calibrated and compensated as to show directly in degrees the temperature of various parts of the engine where thermocouples are installed. The leads from several thermocouples are brought to the indicator through a selector switch. Another device is the sonic altimeter in which a compressed air whistle produces signals electrically timed and controlled, which are reflected from the ground. The echo is heard in a stethoscope and, by means of a timing indicator mounted on the instrument panel, the time interval between outgoing and returning signals is interpreted directly in terms of distance above the ground.

Vertical Transportation

The opening of the Empire State Building in New York City in 1931 placed in service the largest installation of elevators yet made. These are all of the automatic type and those serving the upper part of the tower have higher speeds and longer vertical travel than any previously installed. Improvements in construction and in the control of emergency stopping devices now permit speeds up to 1200 ft. per minute.

An installation of double-deck elevators, serving two floors simultaneously, has been made in the

tower of the new Cities Service Building in New York City. In this same structure there is also the first installation of escalators in an office building, a means of transportation which is being used more and more extensively in department stores, railway stations, etc.

The arrangement, mentioned in last year's report, in which two independent elevators are operated in the same shaft, one running express to the upper floors and the other serving the lower floors, with suitable safety interlocking, appears to be a thoroughly practical development. Such elevators are in service in one of the Westinghouse buildings in East Pittsburgh.

Applications to Marine Work

ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO MARINE WORK*

As in the past few years, the major items of activity of the committee have been:

1. Accumulating, as a result of experience, data for revision of Standards No. 45, Recommended Practise for Electrical Installations on Shipboard.
2. Promoting the idea of establishing a definite status of the electrical operating personnel on shipboard.
3. Following closely installations of electric propulsion and electrification of auxiliaries on shipboard.

Standards No. 45

These standards are proving to be more and more useful to naval architects, shipbuilders, ship operators, and manufacturers of electrically driven auxiliaries. As a result of this increase in use, it is natural that changes and additions should be found desirable. During the past year the committee has continued to collect data for such revisions and when the volume of this data seems to justify a reissue of the standards, the committee expects to recommend such action to the Institute.

Operating Personnel

For some years the committee has felt it important that the personnel in charge of the electrical machinery on ships should have a more definite status than is now in vogue. With the increasing use of electricity for both propulsion and auxiliaries, the necessity for such a recognized status has become more urgent. Our first efforts were based upon improving the status of electrical operating personnel through governmental channels, but as a result of experience, it has become apparent that our efforts will probably meet with more success if we cooperate with the owners and operators of vessels to this end; hence, during the past year we have been in further conferences with the American Steamship Owners Association and we believe that we are about to arrive at such a working agreement with this association as will lead to definite results.

Electric Propulsion and Auxiliaries

As stated in last year's report, the year 1930 was one of great activity, progress and accomplishment in marine engineering, generally. This was due largely to the passage of the Jones-White Merchant Marine Act in 1928. This activity resulted in contracts being let for a large number of ships with electric propulsion and auxiliaries.

Due to the present financial depression the past year has not been marked by such activity, but the program started the year before has continued to be executed without cancellation of contracts.

The following table shows the status during the year of new ships in the U.S.A. equipped with electric propulsion:

Ships Commissioned in the U.S.A. During 1931

Turbine Electric Drive

Name	Type	Horsepower
PRESIDENT HOOVER	Passenger Cargo	26,500
PRESIDENT COOLIDGE	Passenger Cargo	26,500
TALAMANCA	Passenger Cargo	10,500
CAYUGA	Coast Guard Cutter	3,220
SHOSHONE	Coast Guard Cutter	3,220
	Total	69,940

Diesel Electric Drive

Name	Type	Horsepower
COLUMBINE	Lighthouse Tender	240
LINDEN	Lighthouse Tender	240
GULF MIST	Tanker	400
WHITE FLASH	Tanker	375
SAN DIEGO	Ferry	750
DUPLEX	Dredge	600
	Total	2,605

Ships Under Construction in the U.S.A. During 1931

Turbine Electric Drive

Name	Type	Horsepower
*SEGOVIA**	Passenger Cargo	10,500
CHIRIQUI	Passenger Cargo	10,500
ANTIGUA	Passenger Cargo	10,500
QUIRIGUA	Passenger Cargo	10,500
VERAGUA	Passenger Cargo	10,500
	Total	52,500

* Destroyed by fire Dec. 1931.

* COMMITTEE ON APPLICATIONS TO MARINE WORK:

R. A. Beekman, Chairman,

E. C. Alger,	J. E. Kearns,	W. E. Thau,
H. C. Coleman,	Alexander Kennedy, Jr.,	John Van der Dussen,
E. M. Glasgow,	J. B. Lunsford,	A. E. Waller,
H. F. Harvey, Jr.	I. H. Osborne,	O. A. Wilde,
C. J. Henschel,	G. A. Pierce,	J. L. Wilson,
W. Hetherington, Jr.,	W. H. Reed,	R. L. Witham,
H. L. Hibbard,	H. M. Southgate,	W. N. Zippler.

Diesel Electric Drive

Name	Type	Horsepower
——————	3 Tugs	1,600
——————	1 Yacht	600
	Total	2,200

Gasoline Electric Drive

Name	Type	Horsepower
JOHN T. HARVEY	Fireboat	2,130

Production and Application of Light

ANNUAL REPORT OF THE COMMITTEE ON PRODUCTION AND APPLICATION OF LIGHT*

Production of Light

Statistics on Lighting Progress as Indicated by Incandescent Lamp Sales

THE production and use of artificial light, as indicated by the sale of incandescent lamps, decreased slightly during 1931 as compared with previous years. In actual numbers of lamps sold the decrease was not great. The average wattage decreased from 61.2 to 60.9 watts, lamp efficiency from 13.3 to 13.4 lumens per watt and average lumens from 814 to 817.

The continued increase in the use of 120 volts for lighting circuits is notable. The percentage of 120-volt lamps sold increased from 41.3 per cent in 1930 to 43.9 per cent in 1931, while 110- and 115-volt lamps decreased from 5.2 per cent to 3.7 per cent and 48.9 per cent to 48.0 per cent, respectively. The adoption of the three-phase four-wire network system of distribution is probably the major factor influencing this trend.

Street lighting continues to show an increase both in the number of lamps used and in the average light output.

New Incandescent Lamps

Photoflood Lamps

A companion lamp for the photoflash lamp has been developed—the photoflood lamp. The photoflash lamp is intended for use in making snapshots, while the photoflood lamp is intended for time-exposures and for home or amateur motion picture photography. The new lamp has a bulb of the same size and shape as the standard 60-watt lamp but is rated at 250 watts and operates at an extremely high efficiency. In light output it is equivalent to a standard 500-watt lamp but in photographic effect, due to a high percentage of actinic light, it compares with a 750-watt lamp.

Neon-Filled Christmas Tree Lamps

Christmas trees are illuminated usually by strings of eight 15-volt lamps burning in series. The failure of one extinguishes the entire string and it is necessary to try each successive lamp in the string until the burned-out lamp is located. Neon-filled lamps have been developed which operate in the usual manner until one fails. This impresses the full line voltage across that particular lamp and causes it to glow with the characteristic neon red. As the current producing the glow is not sufficient to light the remaining lamps, the burned-out lamp is identified readily.

Inside Frosting 150- to 500-Watt Lamps

The inside frosted finish has been made available for lamps of 150 to 500 watts. This finish is desirable for lamps used in light density enclosing globes and in indirect lighting units since it diffuses the light and eliminates sharp shadows.

Addition of 1,500-Watt Lamps

Increasing use of high intensity illumination produced a demand for 1,500-watt lamps sufficient to warrant their inclusion in the regular lamp schedules.

Elimination of 600- and 800-Lumen Lamps

Authorities on street lighting practise consider the use of lamps of less than 1,000 lumens output inadvisable. The 600- and 800-lumen, 6.6-ampere lamps have been removed, therefore, from the regular schedules.

Imported Incandescent Lamps

Electric lighting in America has enjoyed a favorable lamp situation in that a great majority of the lamps supplied to the public have been of well-controlled quality and of highest practicable efficiency. This condition is threatened now with impairment due to the advent of inferior lamps. Notable among these are lamps imported from Japan and sold through irregular channels of distribution. The committee is informed that aside from miniature

* COMMITTEE ON PRODUCTION AND APPLICATION OF LIGHT:
W. T. Blackwell, Chairman,
J. W. Barker, H. S. Broadbent, J. M. Bryant, W. T. Dempsey, E. E. Dorting, L. A. Hawkins, H. H. Higbie, C. L. Kinsloe, R. D. Mailey, G. S. Merrill, P. S. Millar, P. H. Moon, R. E. Simpson, C. J. Stahl, G. H. Stickney.

›s, about twenty millions of Japanese lamps were ›rted during the last year. These were char-:istically of such low efficiency that at prevailing ; for current the public could not afford to use ı.* Defects which interfere with satisfactory .ce were unduly prevalent among them and their ›erformance was very irregular and inconsistent.

drawing attention to this development, the ›nittee bespeaks cooperation of electrical engi-s generally in doing all that may be practicable revent the impairment of American lighting by ›s of inferior quality.

Base and Socket Standardization

: the present time the screw bases and sockets dard in Europe differ slightly from the original :rican Edison standard in such a way that :rican lamps are not assured of fitting in Euro-ı sockets, but European lamps can be put in :rican sockets, though failing to meet American :y requirements. Although many more Ameri-sockets and bases are in actual use, it was pro-d to adopt the European design as the inter-›nal standard. At a meeting of the Interna-al Electrotechnical Commission's Committee, concurrently with the 1931 sessions of the In-ational Commission on Illumination, the Ameri-standards were recommended on a par with the ›pean and plans were advanced looking toward a le universal standard of intermediate dimensions.

Proper Operating Voltage

he voltage at which incandescent lamps are ated affects their input, output, efficiency, rate of eciation, and cost of producing light to such an nt that it cannot be overlooked in any considera- of the production and application of light in-ing such sources.

he N.E.L.A. Lamp Committee Report for 1930–31* contains a study of operating voltages in use in some 24,590 communities. The detailed figures presented in the report reveal an undesirable tendency toward the increased use of more than one standard voltage in individual communities. Such dual standards make it difficult, if not impossible, to insure that lamps of proper voltage are used. During the five-year period from 1923 to 1928 there was a marked reduction (13.2 per cent to 5.4 per cent) in the extent to which two lighting service voltages were used by any one community, but in the last years this has increased again.

Wiring Specification

Of the specifications mentioned in last year's report, the "Minimum Specification for Wiring of Lighting Circuits in Industrial Structures" was issued during the summer.

Regarding residence wiring, several associations undertook independently the development of specifications. An industry committee was organized to coordinate the work and prepare amplified specifications acceptable to all groups. This work is reported now to be complete, subject to final approval by the several associations. It is understood that the proposed specification sets No. 12 wire as the smallest size to be recommended for any lighting circuit. This limitation, corresponding as it does to that of the commercial and industrial specifications, should help eliminate smaller sized wire from good standing with the designers of electric light wiring, and thus advance good engineering in this field.

Carbon Arcs

Recent careful control tests of various sources of illumination with respect to their speed and color reproduction in photography have shown that the white flame photographic carbon almost exactly duplicates the results obtained with natural sunlight

·ansactions, Illuminating Engineering Society, November 1931.

* N.E.L.A. Bulletin—Sept. 1931, p. 627.

Table I—Data on Incandescent Type of Ultra-Violet Sources

Source	Type S-1	Type S-2	Type G-1 Lamp	CX Lamps 60-watt	CX Lamps 300-watt	CX Lamps 500-watt
ximate lamp watts	400	130	36	60	3000	500
ximate total watts with auxili-s	500	175	50	60	300	500
ximate transformer primary ›eres	9	3	1			
ximate operating volts	14–15	15	18–20	110–115–120*	110–115–120*	110–115–120*
ximate operating amperes	27.5	8.5	2	0.5	2.6	4.3
ximate lumens	8400	1850	150	785	6000	10,750
ximate lumens per watt (lamp)	21	14.2	3.7	13.1	20	21.5
ximate over-all lumens per t	16.8	10.5	3.0	13.1	20	21.5
	PS-22 inside frosted	A-17 clear	A-21 inside frosted	A-21 inside frosted	PS-30 inside frosted	G-38 inside frosted
	Mogul screw	Special screw	Medium screw	Medium screw	Mogul screw	Mogul screw
num over-all length—inches	6 7/16	4 7/8	4 1/4	4 15/16	7 1/8	7 5/8
center length—inches	5	3 3/4	2 3/4**	3 3/8	5	5
:andle minutes for MPE	3500	6500	1300†	175,000†	120,000	100,000
·ximate life—hours	400	400	500	500	500	500
rice	$7.50	$3.75	$3.50	$1.00	$3.00	$3.50

B. Burning the Types S-1 and S-2 lamps at an angle of 45 degrees reduces their ultra-violet outputs 30 and 40%, respectively. Eliminating the wire screen : Type S-1 units increases their output about 20%.

lso available for 28–32 volt circuits.

Since the entire bulb glows this dimension is base contact point to center of bulb which is also the center of the electrodes.

stimated.

and gives a nearly perfect separation of color values in effective shades of gray.

In the field of motion picture projection, carbons have been developed which are steadier in burning and, in certain sizes, even higher in intrinsic brilliancy than those formerly obtained.

Precratering of high intensity positives has resulted in a more rapid burning in of natural craters and full intensity of illumination, as well as a resultant saving in costs by reducing the possibility of mirror or condenser pitting.

For searchlights used in airport floodlighting and military purposes, carbons have been developed which will give from 50 to 100 per cent more light at 225 and 250 amperes than has been possible previously with regular searchlight carbons.

Ultra-Violet—Incandescent Type

Last year's report mentioned the introduction of four new sources of ultra-violet radiation emitting little or no wavelength shorter than 2,800 and, therefore, safe for use in the home, the school, office, et cetera; *i. e.*, the Types S-1 and S-2 lamps, the Type G-1 or glow lamp and the CX lamps.

Considerable improvement has been made in these sources since their introduction. The essential technical data pertaining to them are given in Table I.

During the year very complete lines of fixtures have been placed on the market for the Types S-1 and S-2 lamps. Suspension and ceiling type units have been developed which have a spread of both the ultra-violet radiation and the visible light flux. Such units are finding wide application in places where the exposure periods are somewhat limited, such as in swimming pools, gymnasiums, hospital solariums, lunch and recreation rooms, et cetera.

For use in offices, schools, et cetera, where it is desired to combine the health maintenance value of ultra-violet radiation with the lighting over exposure periods of 6 to 10 hours, a third line of equipment, known as dual-purpose lighting fixtures, has been developed. Most of these utilize regular incandescent lamps for indirect or semi-indirect lighting and also an ultra-violet lamp and reflector so designed as to spread a mild intensity of ultra-violet over a wide area.

Gaseous Tube Electric Illuminants

It has long been felt that possibilities of materially higher efficiency of light production lie in the domain of electrical discharge through gases rather than in incandescence. While incandescent lamps, with which most artificial lighting is accomplished, are serving the purpose exceedingly well, despite limitations of theoretical low efficiency of light production, and are undergoing gradual evolution which appears to bring them closer and closer to the limits of the possibilities of production of light by incandescence, the engineering world is favorably predisposed toward the idea of achieving efficiencies of a higher order from gaseous tube illuminants.

The present low-voltage gaseous and mercury-vapor arc tubes make available to the illuminating engineer additional lighting tools having characteristics that possess value for particular purposes. Thus the mercury arc lamp, with its characteristic green-blue light, provides a "work light" which has peculiar value for certain industrial applications. The arc tubes of neon or other gases, with their characteristic instantaneous response to electrical discharge, are especially useful in television, stroboscopic work, et cetera. Further, the vivid colors of these tube illuminants make them applicable for certain special uses, such as aircraft beacons, and for publicity purposes. These sources, however, are of the same order of efficiency as tungsten filament lamps.

Beyond these developments the committee has information only of experimental developments in low voltage gaseous arc tube sources. Among these the highest efficiencies of light production attained are in tubes of high power. Pirani's oft-cited sodium tube of special sodium-resistant glass, heated independently to 350 deg. cent. and enclosed within an outer evacuated tube, is said to attain 70 lumens per watt applied to the tube itself. It produces light of a brilliant yellow color. No data are available as to the power required for the complete equipment. Neon and mercury-vapor low-voltage arc tubes, three or more feet in length and consuming 1,000 to 2,000 watts, are said to attain to 35 to 50 lumens per watt. In smaller sizes of lower power input very much lower efficiencies of light production are attained.

In the opinion of the committee attempts to develop gaseous arc tube light sources of a materially higher efficiency than modern incandescent lamps are interesting and perhaps promising. Of practical achievement in the way of commercially applicable illuminants the committee has nothing new to report at this time.

Application of Light

New and Improved Incandescent Lamp Equipment

The standard dome reflector and the glassteel diffuser remain as standard lighting equipment for industrial areas. Recent developments have improved the methods of hanging these reflectors so as to reduce the time required and the cost of cleaning and relamping. The high intensities of light required on certain working areas can be secured by the use of recently developed industrial projectors which can be mounted on the ceiling, side walls or columns and adjusted to project the light in any desired direction.

A totally enclosed semi-indirect lighting unit has been developed with the bottom of the bowl of high density glass and the top portion practically clear. This type of glass makes a highly efficient unit and one easily maintained.

Appearance of the lighting equipment is playing a very important part in commercial installations. The contours of enclosing globe units are more pleasing in design and hangers are receiving considerable attention from the design standpoint. An interesting development in the indirect type of unit is

one constructed entirely of metal louvers which can be obtained in a variety of color finishes.

Outdoor lighting such as the floodlighting of buildings and areas devoted to outdoor sports is increasing in popularity. This is partly due to the development of more efficient floodlight projectors and the introduction of open type floodlights. Many manufacturers have discarded the plain parabolic mirror for compound curves forming 2 and 3 surface mirrors. This increases the efficiency and permits accurate control of the beam.

The floodlighting of homes for holiday decorations, and gardens during the summertime, is now made possible by the development of small floodlight projectors designed for use with 100- and 150- watt lamps.

Street Lighting

Street lighting has been referred to frequently, by engineers, as the application of electric light where the practise has lagged most behind growing needs. During the year the demand for smaller municipal expenditures has been reflected in numerous proposals for reduced street lighting. Considerable apprehension was felt by experts lest serious increases in traffic and crime hazards should be incurred for only negligible savings. So far no extensive reduction has been made and several cities, where reduced lighting was tried, returned promptly to former illumination. On the other hand there has been a definite arrest in the advance of street lighting.

Group Replacement of Lamps

Since incandescent lamps operate with almost no attention and a substantial proportion of them last beyond their economic efficiency, many installations fall below their proper illumination performance. The obvious cure is systematic cleaning and replacement at suitable intervals. A recent awakening to the importance of such practises is showing good results. Already about thirty utility companies are applying "group replacement" to their street lighting. Noticeable improvement in illumination and reduced outages are being secured at little, if any, increased expense. Similar methods are applicable to traffic signals, large buildings, large signs, and wherever lamps are grouped in sufficient numbers to permit economic organization of maintenance.

In connection with group replacement, it is desirable to segregate used lamps which have considerable life expectancy from those which are approaching failure. This is facilitated for clear bulb lamps by a new inspection box, which reveals filament defects.

Railway Signals in Locomotive Cabs

Many serious accidents on railroads have resulted from failure of the engine crew to see signals. A new system, being applied extensively by a leading railroad, has a light signal in a conspicuous position in the locomotive cab, where it is independent of weather conditions and its view not limited to a fleeting glance. A sound device calls special attention to changes. The enhancement of safety is obvious.

Sports Lighting

The increasing popularity of artificial illumination in this field is due to the use of more adequate levels of lighting. For example, in football fields about 15 foot-candles have been found to be desirable in contrast to the 5 to 7 foot-candles often recommended in the past. For baseball fields a consumption of about 300 kw. is considered necessary now, whereas 200 kw. was about the maximum of former attempts.

Lighting of Buildings Exteriors

The application of artificial light to the exterior of buildings is making rapid progress, especially in the endeavor to create artistic night-time effects. Lighting effects formerly obtaining only by floodlighting are, in some of the newer buildings, being improved upon by novel methods. Today architects are designing buildings with the idea of artistically lighting the exteriors at night. They are paying attention to the direction of light projection and so designing as to create night-time as well as day-time effects on their buildings. One development is the use of luminous panels built into the façade of the building. Pilasters of diffusing glass behind which are mounted various colored lamps connected to dimmers produce changing color effects. Entire façades are covered with panels of this sort or constructed of glass brick which can be illuminated from behind at night. The development is following gradually that of built-in lighting for interior use.

Built-In Lighting

It is illogical to wait until a building is completed before considering lighting equipment, yet in the past this was generally the case. Now, fortunately, in most new structures the artificial lighting is designed as a component part of the interior. Manufacturers of diffusing material, such as glass, molded plaques and translucent substances, have made available many new varieties and these are finding application. Conventional fixtures designed on traditional lines are passing rapidly from the picture.

Residential Lighting

While the number of newly electrified homes in 1931 decreased to one-seventh the number added in 1930 and to one-seventeenth the number added in 1929, the consumption of electrical energy in homes showed an increase of approximately 8 per cent in 1931, only three or four points less than the increase in previous years when new residential building was at high levels. Decreasing hours spent in the various places of entertainment outside of the home have

meant increasing evening hours at home for all members of the family, calling for a greater use of electric light.

The portable lamp has grown in popularity as is evidenced by the increasing number of styles and designs which have been produced. The indirect portable lamp using a 200- or 300-watt lamp has not usurped this field although it has continued to grow in numbers. Decorative floor and table lamps using the Type S-2 lamp have made their initial appearance.

Lighting fixtures providing indirect or semi-indirect lighting and selling at very low prices have been received favorably in various parts of the country for the relighting of certain rooms of the homes of "minimum bill" customers. The design of these fixtures is such that they may be fastened directly to existing single sockets.

The President's Conference on Home Building and Home Ownership devoted a section of its Fundamental Equipment Report to the Wiring and Lighting of the Home, giving attention to these home modernizers equal to that devoted to such items as heating, ventilating, and plumbing.

Automobile Lighting

By means of a three-filament headlamp, a lighting system has been developed giving an asymmetrical distribution of light with reference to the car axis in which more light is directed to the right side of the road, particularly when passing another car. This system is so arranged that a city-driving and a country-driving range of light control is provided.

The advantages of directing more light to the right when passing are well recognized and several auxiliary lighting units are available which when used in connection with the present standard dual beam system provide this desirable passing light.

On some cars the fender lights serve a dual purpose, the switch control being so arranged that in addition to acting as marker lights when the car is parked these fender lamps are lighted when the beam is depressed, thus showing the oncoming driver that the depressed beam is being used and giving in addition an indication of the extreme width of the car.

Two rear lamps are being supplied for many current model motor cars. These lamps are generally a combination rear and signal unit. The majority of rear units are equipped with reflex glass which gives an indication from the reflected light thrown on it. The use of reflex materials in conjunction with incandescent lamps is considered desirable from a safety standpoint. Incandescent lamps are being used also to indicate when the engine needs oil and whether or not the battery is being charged.

Present day headlamp equipment, which is mostly of the fixed focus type, is capable of furnishing good road illumination with a minimum of glare but in order to obtain the maximum advantage from this equipment additional educational work is still needed which should be directed along the lines of encouraging car drivers to use the lower or depressed beam when meeting or signaled by oncoming cars.

Daylight vs. Artificial Light

Recently developed lighting equipment provides artificial light with supplementary ultra-violet radiation, exceeding that received from daylight filtered through window glass. This, coupled with improved electrical air conditioning, is rendering building construction independent of natural illumination. In a number of buildings recently completed or under construction, daylight has been purposely excluded.

Architectural Relations

Each year architects show a growing interest in the decorative as well as utilitarian possibilities of modern lighting. The Illuminating Engineering Society, in cooperation with the Beaux-Arts Institute of Design, has established an Illuminating Engineering Society Prize for which architectural students throughout the country compete. This year's project is designing the lighting for an exhibition hall at a world's fair. It is planned to continue this prize competition for the next decade.

The American Institute of Architects is cooperating with the Illuminating Engineering Society in the revision of the American Standard Code of School Lighting.

Light Control

The photoelectric light control relay is a device which regulates automatically the turning on and off of artificial lighting as the intensity of daylight decreases or increases. During the year such control was applied to the lighting of a school room where children in a special "sight-saving" class receive their instruction. Tests conducted in this room indicated that in order to maintain an intensity of 15 foot-candles, it is necessary to use the artificial lights at least 30 per cent of the time the room is in use.

Thyratron control of lighting is being applied to theaters, floodlighting of buildings, show windows, and electric fountains.

Thermionic tubes appear especially applicable for automatic dimming controls, where the only moving part can be small potentiometers or phase shifters actuated by very small motors. Applications of mobile color lighting with these controls include a floodlighted building, dance halls, night clubs, restaurants, and a number of theaters.

One of the most recent developments utilizes a continuous belt for controlling the potentiometer adjustment by providing a conducting path for each color or group of lights to be controlled. Any desired combination can be secured by varying the position of the conducting paths on the belt, so that any predetermined lighting effect can be repeated at will, or a new combination can be secured by "changing the roll." It is reported that the first installation of this arrangement will be to control the lighting of Buckingham Fountain in Chicago.

With the new thermionic tube controls the manual switchboard for theater and stage lighting can be very small, located in the orchestra pit, on the stage, or

even in the front rows of the orchestra. Now the "lighting conductor" becomes a reality and the lighting of the show is played by the conductor who sees and hears the entire action.

Illuminometer

A new portable illuminometer employing the photoelectric principle has become available. The photonic cell consists of a disk on which has been deposited light-sensitive material so that, when exposed to light, a slight but apparently constant electrical potential is generated. The readings are made on a microammeter connected to the cell by means of a flexible conductor cord.

For increased deflections two or more cells are sometimes mounted in a single housing and connected in multiple. Measurements and checks under incandescent lighting of the range ordinarily found indoors seem to show comparatively close agreement with the usual types of visual illuminometers.

Lighting Plans for 1933 Chicago Fair

A wide interest and curiosity has been exhibited by the public regarding the illumination of the 1933 Fair. It is not appreciated generally that the interiors of the Fair buildings will have no natural light. They will be illuminated both day and night by electricity. In general there are no windows or other openings through which natural light may enter.

One novelty will be shimmering effects on exterior walls such as is produced by reflection of the sun's rays from bodies of water in the daytime. A lighting projector built upon this principle will be used to throw fantastic moving color patterns on building walls. By agitation of the water in different ways, patterns of various forms may be produced. So-called scintillators will be used also. In this case squares of polished metal trembling on delicate supports will flash dancing color patterns over large areas of frosted glass. This is one of the few lighting effects that can be utilized in the daytime. The rays of the sun are allowed to penetrate the glass at many points and are reflected back by the metal squares in lively fashion, somewhat similar to the heliograph used by the Army for signal purposes.

Fluorescence will be used also. Many objects such as flowers, foliage, statuary, et cetera, will be treated with fluorescent materials and under so-called invisible light will appear in contrast with the surrounding foliage.

The possibility of fluorescent fountains has not been overlooked. There are several organic substances that may be added to water to produce fluorescence, such as eosine, fluorescene, and aesculin. Very small quantities of these substances added to water in a circulating fountain are sufficient to impart a mysterious glow to the water under so-called invisible light.

During the last few months the Fair has been experimenting with a great so-called flaming ladder arc, using a potential of 33,000 volts. Rising from a huge outdoor transformer will be two electrodes about thirty feet high. A flaming arc will start from the bottom of these electrodes and travel upward. As this intense flame dissipates at the top, another automatically starts at the bottom, so that there is a succession of fiery bridges or rungs in constant motion. Hence the term "ladder arc." As these arcs travel upward, dry chemical salts are injected by compressed air. These salts impart changing colors to the arc stream.

International Commission on Illumination

The International Commission on Illumination met in Cambridge, England, the week of September 13, 1931. In connection with the meeting a Congress was held in which meetings assembled in London, Glasgow, Edinburgh, Sheffield, Buxton, and Birmingham. Many notable demonstrations of illumination were made for these events and the subsequent celebration of the Faraday Centenary, among which were the lighting of the public buildings and streets of London and Edinburgh Castle. Excellent progress was made toward international understanding on illumination problems.

A new topic was Aviation Lighting in which international unity is especially important.

General

Revised Nomenclature and Standards

During 1931 there has been widely circulated for discussion and criticism a revised set of terms and definitions to supersede the American Standard "Illuminating Engineering Nomenclature and Photometric Standards" issued in 1925. The changes which have resulted from this discussion are largely matters of form rather than of substance. The new edition of the nomenclature will show, therefore, few radical departures from the established practise, but is believed to be somewhat more clear and logical.

Primary Standards of Light

International discussion of fundamental photometric problems has continued and several laboratories abroad are reported to have in progress experimental tests of the form of primary standard proposed by the Bureau of Standards. This standard consists of a refractory tube immersed in molten platinum at its freezing temperature. The tube is so constructed and observed as to be a "complete radiator" or "black body." Its brightness as found at the Bureau of Standards is 58.85 candles per square centimeter. The question of accepting this standard is before the International Commission on Illumination and the International Committee of Weights and Measures, but a decision must await independent

confirmation of the Bureau's results by some other national laboratories.

DEATH OF THOMAS A. EDISON

The Committee on Production and Application of Light cannot conclude its report without allusion to the passing of the founder of the electric lighting industry. His death on October 18, 1931, was the signal for an expression of worldwide appreciation of the services and of the life of the man whom electrical engineers have held in high regard by reason of his inauguration of electric light and power as a widespread service to the public. Edison passes but his work goes on. He lives in the esteem of those who carry on under the banner which he raised.

Applications to Mining Work

ANNUAL REPORT OF THE COMMITTEE ON APPLICATIONS TO MINE WORK*

THE past year has been one of very greatly reduced activity in all classes of mines. New machines and new applications of electricity in mining work have been few and, generally, of a minor nature. There has, of course, been no incentive to force production or to increase the capacity of mines, and labor-saving devices have not been in demand because of an unwillingness on the part of operators to aggravate the bad unemployment situation. However, there have been some installations and devices worthy of comment.

A West Virginia coal mine has installed a passenger elevator to expedite the movement of men in and out of the mine and to relieve the production hoist of this service so that it can continue in its regular duty. This elevator has all of the safety and control features of a high-speed traction-drive office elevator. It handles twenty men per trip in a shaft 347 feet deep at a speed of 450 feet per minute. As this elevator travels in the intake air compartment, the car has certain special structural features to permit an uninterrupted flow of air.

Some companies have found it profitable to operate their mines only at night to secure a lower rate for electric power at the off-peak period. Power economies have also been effected by the use of power demand limiters. An installation of capacitors for power factor correction has shown a return of approximately 7 per cent per month.

Two new electric cap lamps for use in gaseous mines have been developed. One of these, weighing only 63 ounces, gives a beam candlepower of 26 at the beginning of a shift and the other, which weighs only 87 ounces, gives a beam candlepower of 55 at the beginning of the shift. A flood lamp, particularly designed for lighting the face for cutting and loading, gives a beam candlepower of approximately 350. All of these lamps have been approved by the U. S. Bureau of Mines.

Improved performance is being regularly obtained from cutting and loading machines. One operator reports that a cutting machine regularly cuts 1,000 to 1,200 tons in 6 to 7 foot coal in a shift, and that he is regularly obtaining 375 tons per day from his loading machine.

A Western Pennsylvania mine has installed a system of automatic door control, using "the electric eye" as the controlling relay. The mine doors are caused to open and close in proper sequence for either direction of movement of the trip.

A wound-rotor induction motor with direct-current excitation of the primary has been installed as a braking generator to replace mechanical brakes, holding a rope haul trip at proper speed down grade. The high expense of brake maintenance has been practically eliminated.

Several large induction motors and synchronous motors with automatic line-start control have been installed for pumping in the anthracite field. The controls for several of these are housed in cubicles and completely erected at the factory.

A large, high-speed, heavy-duty, variable-voltage hoist, taking its power from a synchronous motor-generator set, has been installed in Canada. The rotating equipment consists of a 1,250-kw. generator, an 1,800-hp., 750-r.p.m. synchronous motor and a 1,550-hp., 68-r.p.m. hoist motor. The skip has a capacity of 6 tons of rock per trip and travels at a speed of 2,200 feet per minute.

A new light-weight self-propelled cutting machine has shown favorable results over several months of trial. The machine has a very high-speed cutter which resembles in its operation a band saw more than the usual type of cutter.

The construction of new coal-cleaning equipment kept pace with progress of previous years in this line. It is estimated that 8,000 tons per hour of complete mechanical cleaning capacity were installed in 1931 in addition to 20,000 tons of capacity for cleaning and sizing. All of these tipples and cleaning plants were, of course, electrically driven.

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* COMMITTEE ON APPLICATIONS TO MINING WORK:

D. E. Renshaw, Chairman,
A. R. Anderson, L. H. James, C. W. Parkhurst,
Graham Bright, J. E. Kearns, F. L. Stone,
J. H. Edwards, Carl Lee, J. F. Wiggert,
E. J. Gealy, W. H. Lesser, C. D. Woodward.
L. C. Ilsley,

Transmission and Distribution

ANNUAL REPORT OF COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION*

THE activities of the Committee on Power Transmission and Distribution have continued through the past year along the lines organized in previous years. Various subjects of interest to the Institute membership have been treated in a number of papers presented before the conventions and district meetings.

A brief outline of the activities of the several subcommittees follows:

Subcommittee on Steel Transmission Towers and Conductors

Subjects relating to steel towers have been studied and certain items of general interest are now being given particular attention preliminary to the preparation of future reports.

A report has been drafted outlining the requirements for modern steel tower transmission lines which, after review, it is expected will be published. Conductor vibration has been given intensive study. A direct result of this work has been the publishing of a bibliography including all available data on the subject of vibration. A session at the Summer Convention is devoted to this important subject.

Subcommittee on Distribution

Continued consideration has been given to the various broader aspects of distribution, including developments in secondary and primary networks.

Of particular interest to distribution engineers is the symposium presented at the Winter Convention consisting of six papers on distribution circuit lightning protection. This symposium summarized the results of intensive field and laboratory experimental work and analyses of operating experience. It is believed that this material will be productive of improvement in distribution equipment and construction practises and in service reliability.

Subcommittee on Cable Developments

There have been no marked innovations in the cable art during the past year, although study has been continued on the developments indicated in previous reports. In the high voltage transmission cable field, the highest voltage submarine cable crossing in the world, across the Columbia River near Portland, Oregon, is also the first of the oil-filled type used in submarine work. The cables are 750,000-cir. mil., single-conductor, rated at 115 kv., and an insulation thickness of 0.550 inch. An unusual feature is the use of hard-drawn-copper armor wires, instead of the usual steel, in order to reduce the losses in the armor and thereby increase the rating to 114,000 kva.; over 30 per cent more than if steel armor had been utilized.

The performance of experimental installations of 132-kv. cables, one of the oil-filled type with reduced insulation and the other of the solid type, in Chicago and in Newark, respectively, has continued to be successful.

Subcommittee on Interconnection and Stability

The joint subcommittee on interconnection is formed from representatives of the Power Generation, Protective Devices and Power Transmission and Distribution committees. During the year the scope of the committee was increased and representatives were added from the Committee on Electrical Machinery.

This joint subcommittee sponsored a session at the Winter Convention on the subject of Decrement Curves and Power System Stability. Two other stability papers were presented during the year.

Subcommittee on Lightning and Insulators

The necessity for establishing a definite wave or group of waves by which to measure impulse strength of insulators has been recognized for some time. In the interest of greater uniformity in test practises, agreement has been reached on a tentative group of waves (1) which would closely approximate the effects of natural lightning voltages imposed on apparatus connected to transmission systems; (2) which could be produced with available laboratory equipment; and (3) on which considerable impulse data have already been secured by various laboratories which have been investigating the performance of insulation under impulse voltages. The following three waves have been agreed upon as preferred test waves for impulse testing. These waves are designated as $^1/_2$ x 5, 1 x 10, and $1^1/_2$ x 40. The first number indicates the microsecond time to crest, and the second number the time in microseconds from zero to 50 per cent of crest on the tail.

Another development in the lightning field has been continued this year in the factory test of commercial transformers with artificial impulse waves. It appears that the manufacturers are now in a position to test commercial transformers in the higher voltage ranges with artificial impulse waves, and a recommendation has been made that a committee formulate the procedure to be followed in applying

* COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION:

P. H. Chase, Chairman,
L. N. Conwell, Vice-Chairman,
T. A. Worcester, Secretary,

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F. E. Andrews,	K. A. Hawley,	D. M. Simmons,
A. B. Campbell,	L. F. Hickernell,	C. T. Sinclair,
C. V. Christie,	D. C. Jackson, Jr.,	L. G. Smith,
A. E. Davison,	J. P. Jollyman,	H. H. Spencer,
H. C. Dean,	A. H. Lawton,	Philip Sporn,
L. L. Elden,	I. E. Moultrop,	W. K. Vanderpoel,
R. D. Evans,	L. L. Perry,	C. F. Wagner,
F. M. Farmer,	T. F. Peterson,	H. S. Warren.
T. H. Haines,	D. W. Roper,	

impulse waves to transformers. This work is already in progress.

Field investigation of natural lightning which has been in progress for the last few years has been continued on a decreased scale.

Discrepancies in 60-cycle flashover values of insulators mentioned in last year's report as due to humidity conditions have been further studied this year. Papers fully covering this subject have been presented before the Institute during the year.

Reference has been made above to the field, laboratory, and operating investigations relating particularly to 2,300- and 4,000-volt distribution lightning protection. Of particular interest is the apparent benefit to be derived from interconnecting the primary arrester ground with the secondary neutral, if the latter is well grounded.

Conclusions

In conclusion, the committee wishes to express its gratification at the interest evidenced in the field of Power Transmission and Distribution by the papers submitted and by the attendance and discussion when presented.

This interest together with that displayed by the members of the committee, and by those associated in the work of its subcommittees, have made possible the accomplishments of the committee.

Power Generation

ANNUAL REPORT OF THE COMMITTEE ON POWER GENERATION*

ALTHOUGH the past year has recorded no major strides in power plant design and construction not heretofore discussed in committee reports, the committee has been successful in obtaining a variety of papers of a critical nature for Institute presentation, surveying present practise, with the object of indicating probable lines of advance when the construction of new or additional power projects again becomes active. Following the custom of preparing progress reports only at biennial intervals, the committee report for the past year will merely recount briefly the results accomplished by the several subcommittees engaged in planning and securing technical papers.

The Joint Interconnection Subcommittee, of which F. C. Hanker served as chairman, was instrumental in presenting at the Winter Convention six papers embracing several phases of the subject of stability of power systems, including that of *Stability of Conowingo Hydroelectric System*, by R. A. Hentz and J. W. Jones. A record of the most recent technical advances in power system design and operation was given in that paper. Another valuable paper concerned the standardization of nomenclature regarding stability, being a report by H. K. Sels.

Another session at the Winter Convention was sponsored by the subcommittee on Power Station Auxiliaries, composed of H. W. Leitch and F. H. Hollister. The comparative merits of steam and electric drives for steam power stations were analyzed in papers by W. Poole Dryer and L. W. Smith, advocating opposing views, and in a summary statement by F. H. Hollister.

A subcommittee headed by N. E. Funk has arranged a symposium of four papers on *Combined Economy and Reliability in Operation of Large Electric Systems*, for the Summer Convention. Current practise in the Boston, Chicago, Detroit, and Philadelphia areas will be discussed at that time.

Other work consisted of a review by I. E. Moultrop and J. B. Crane of the economics of the design and use of high-temperature and high-pressure steam equipment, with a supplementary discussion of the use of welding in modern fabrication methods. A paper on this subject awaits opportunity for presentation. The subcommittee on Hydroelectric Practise, J. P. Hogan, chairman, will offer a paper by A. V. Karpov on *Low-Head Hydroelectric Developments* at a Fall District Meeting featuring other papers on hydroelectric subjects. F. A. Annett of the subcommittee on the Design of New Plants has reviewed papers describing the Waukegan and Ashtabula plants, and has cooperated in having the subject of power generation adequately represented on the program of the Pacific Coast Convention this summer.

The Committee recommends that the recent innovations in the design and application of switching structures at power plants be given major attention during the coming year. For that purpose a subcommittee, A. E. Silver, chairman, was appointed which has been assembling data and information for a discussion of that topic next winter.

The Committee wishes to take this opportunity to record its thanks for the assistance given by the several authors and the many discussers of papers to the end that the progress in the field of Power Generation be adequately reported by the committee.

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* COMMITTEE ON POWER GENERATION:

J. R. Baker, Chairman,

F. A. Allner,	W. S. Gorsuch,	E. B. Meyer,
F. A. Annett,	F. C. Hanker,	I. E. Moultrop,
D. S. Brown,	L. F. Harza,	F. A. Scheffler,
Andrew Carnegie,	J. P. Hogan,	F. O. Schnure,
J. B. Crane,	F. H. Hollister,	R. E. B. Sharpe,
E. A. Crellin,	A. H. Hull,	A. E. Silver,
R. D. DeWolf,	H. W. Leitch,	A. R. Smith,
W. P. Dryer,	A. H. Lovell,	E C. Stone.
N. E. Funk,		

General Power Applications

ANNUAL REPORT OF COMMITTEE ON GENERAL POWER APPLICATIONS*

DURING the past year the committee has not sponsored a session at any of the meetings or conventions, but has reviewed and reported upon a number of industrial papers. Two of these papers were presented at the Pacific Coast convention at Lake Tahoe, August 1931, and as far as we know these were the only industrial papers presented at district meetings before the Institute during the year. These two papers are as follows:

Electrical Equipment for Oil Field Operations, by H. C. Hill and J. B. SeLegue

Electric Power in the Wood Products Industry, by C. E. Carey and K. L. Howe

Although the general activity of practically all industrial plants and machinery manufacturers has been greatly curtailed during the year, nevertheless, this extremely competitive situation is responsible to some extent for a number of developments and improvements in industrial equipment which have been brought out. Last year we mentioned the interest that was being shown in connection with the use of electronic tubes for industrial applications. The various characteristics which these tubes possess which are not otherwise obtainable are almost daily finding new industrial uses. A large number of these applications fall under the classification of process control and are in line with the trend of the times toward elimination of waste, reduction of cost, and more accurate control of all manufacturing processes. Most of these electronic developments are given publicity in the various trade papers or in *Electronics* and to keep posted on such activities constant contact with such literature is necessary. A comprehensive review in a report of this kind is entirely impossible.

During the year considerable attention has been given by various electrical machinery manufacturers to the design and construction of motors, controllers, safety switches, push-buttons, and other details to meet the requirements for Class II Hazardous Locations as defined by the Underwriters' Laboratory. Such equipment, although required for such locations in flour mills, grain elevators, starch plants, coal pulverizing plants, etc., finds numerous other desirable applications where its installation results in lower maintenance cost and improved operating conditions.

Instead of attempting to abstract information regarding the numerous developments in industrial apparatus or application, the committee feels that members interested in such equipment can readily obtain such information directly and more completely from the various periodicals as, for instance, *The Electrical World*, *Maintenance Engineering*, *G. E. Review* or *Electric Journal*, together with the various specific industry magazines. The January issue of such magazines generally contains a review of the year's achievements in a much more complete and interesting form than could be given in a report of this kind.

* COMMITTEE ON GENERAL POWER APPLICATIONS:

C. W. Drake, Chairman,
A. H. Albrecht, E. A. Armstrong, James Clark, Jr., J. F. Gaskill, John Grotzinger, Truman Hibbard, Fraser Jeffrey, A. M. MacCutcheon, H. A. Maxfield, John Morse, N. L. Mortensen, A. M. Perry, D. M. Petty, H. W. Rogers, L. D. Rowell, W. K. Vanderpoel, M. R. Woodward.

Iron and Steel Production

ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO IRON AND STEEL PRODUCTION*

General

IT is estimated that the steel industry expended approximately 35 million dollars in 1931 for the purchase and installation of new apparatus, the maintenance of old equipment, and in the purchase or generation of electric power.

During the year there were purchased 63 main-drive motors of more than 300 rated hp. each. The total rated horsepower of these drives aggregated 119,325 hp. These figures compare with the installation of 163,490 hp. which occurred in the year 1930.

A major trend toward increased use of refined control equipment for automatically performing tasks which had previously required manual labor was continued during this year. While such equipment was installed at a reduced rate in 1931, the percentage of men whose duties were no longer required in the steel industry due to such automatic devices increased.

* COMMITTEE ON APPLICATIONS TO IRON AND STEEL PRODUCTION:

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Main and Auxiliary Drives

The 44-inch universal slabbing mill in the Chicago District, referred to in last year's report as being under construction, was completed during the early part of 1931. The upper and lower main horizontal rolls are driven by two 5,000-hp., 40/80-r.p.m., 700-volt, double-armature reversing motors, and the auxiliary vertical rolls are driven by a 2,500-hp., 79/225-r.p.m., 700-volt, single-armature reversing motor. The total continuous capacity of the three motors is 12,500 hp., and the maximum emergency capacity about 35,000 hp., nearly a third greater than any similar mill. The three motors are connected in parallel and are supplied with variable-voltage direct-current power from a 10,500-kw., 5-unit, six-bearing flywheel motor-generator set, consisting of three 3,500-kw., 700-volt generators, a 6,500-hp., three-phase, 25-cycle, 6,600-volt, 370-r.p.m. wound-rotor induction motor and a 180,000-lb. flywheel. When running at synchronous speed, the total stored energy in the rotating parts of the motor-generator set is approximately 270,000 hp-seconds. Latest operating data indicate this installation has proved quite successful.

A recent installation of induction motors and control for operating "catcher tables" has fulfilled the expectations of not only the operators, but of the mill designers and electrical manufacturers as well. These tables are used in the rolling of sheet steel and take the place of the older manual methods of handling the sheets and packs during the rolling process. The cycle of operations includes carrying the material into the mill by means of the roller table, receiving it on the catcher table, tilting the tables upward, transferring the sheet over the top roll back to the roller table, returning the tables to the down position, and reversing the direction of travel back into the mill. This cycle of operation must be completed under some circumstances in three seconds, which means that the motors must be capable of reversing or starting at the rate of 40 times per minute.

Special low-inertia, low-speed motors have been developed to cover this type of application. The speeds used are 375 r.p.m. for 25-cycle supply and 450 r. p. m. for 60-cycle supply. The use of squirrel-cage motors for such duties as this has been attempted only within the past two years, but it is an indication of the changing trend toward the application of simplified motor and control apparatus. Formerly, direct-current mill-type motors were thought the only solution for such problems.

During 1931, the first American installation for producing seamless steel tubes by the "push bench method" was completed. In the production of seamless steel tubing by this method, a heated blank is placed in a hydraulic press and formed into the shape of a thick walled thimble. The thimble is then placed on the end of a mandrel and forced through a series of stationary ring dies, which gradually decreases the wall thickness, and at the same time elongates the thimble, thus forming a long tube with a closed end. After the elongated thimble has been forced by the mandrel through the various dies, the mandrel is withdrawn and the closed end of the tube sawed off. Sizing and finishing is carried on subsequently in mills of the usual design. The power required on this application is approximately the same as that used by the piercing process.

In the installation just completed, the mandrel is forced forward through the dies by means of a rack and pinion which is driven by a 1,500-hp. variable-speed d-c. reversing motor. The control for this equipment is so arranged that upon indications from the operator, the motor will start, accelerate the ram, force the material through the dies at a predetermined rate of speed, then stop, reverse, and return the mandrel to the initial position. Means are provided for adjusting the speed of the stroke over a wide range, and extremely fast acceleration and retardation are necessary to meet the operating cycle. Devices are arranged in connection with this control to prevent the ram from overrunning in either direction. The manufacture of tubes by this process is expected to produce a small seamless tube at very low cost and for this reason it is probable that additional installations of similar equipment will follow.

Two steam engine drives in the Pittsburgh District were replaced by motor drives. A three-high roughing mill driven by a 1,500-hp. steam engine has been re-equipped with a 1,600-hp. wound-rotor induction motor. Likewise a reversing steam engine on a two-high finishing mill has been replaced by a 1,250-hp., d-c. reversing motor. This reversing equipment is said to be one of the smallest applications in the steel industry of reversing main roll drive equipment.

There have been two major hot strip mill installations made during the year. One of these consists of a 72-inch continuous hot strip mill and the other a 76-inch continuous hot strip mill. It is understood that both of these mills are equipped with anti-friction bearings on the main rolls throughout, and combine the use of induction motors on the preliminary stands, synchronous motors on the intermediate stands and d-c. adjustable-speed motors on the finishing stands. It is unusual to find the three types of main roll drive combined in one mill installation, but it was possible on these particular mills to secure the necessary relations between peripheral roll speeds without the use of expensive adjustable-speed d-c. drives throughout the entire mill.

The largest motor equipment ever sold for driving a cold strip mill was also installed during the year. Each of the two stands of this cold strip mill are driven by a 1,500-hp. adjustable-speed, d-c. motor. A tension reel driven by a 400-hp., adjustable-speed, d-c. motor, receives the material from the two cold roll stands. It is apparent that the year has witnessed a change in the electrical equipment used in the rolling of both hot and cold strip.

New designs of electric contactors were announced by one of the leading manufacturers during the year. Decided progress was made by a committee of steel mill engineers toward the standardization of control equipment. It is felt that it will be but a short time until a satisfactory steel mill control standard will be an accomplished fact.

Several new tension-limiting devices were designed

for automatic reeling applications. Some are designed to place a predetermined tension on reels coiling strips after they are rolled, while others are between stands of the finishing passes. Automatic screw-down equipment for two-high and universal mills of simplified design appeared. This apparatus uses electron tubes to replace cumbersome limit switches. However, no installations of this type of screw-down control have been completed at the time this is written. Automatic screw-down control assures uniformity in rolling practise, independent of the whim of the operators, and has resulted in a material improvement in the quality of the product of rolling mills where it has been in service. The apparatus used in the past has been quite complicated and it is felt that the new devices tending to simplify this type of equipment will prove to be a worthwhile development and result in more general use.

Synchronous Motor Control

The recent remarkable increase in the use of synchronous motors in steel mills has made their characteristics, operation, and control a subject of great interest to steel mill electrical engineers. The favorable status of the modern synchronous motor was not achieved, however, until definite limitations of the earlier designs were overcome. Modern design and construction have removed most of these earlier limitations until now the synchronous motor starting, pull-in, and pull-out torques are exceptionally favorable for applications heretofore reserved for induction and direct-current motors.

A recent development of unusual interest has taken place in control systems for synchronous motors. This development is the culmination of investigations started many years ago which have done much to extend the field of application of the synchronous type motor. Recent systems of control automatically start the motors under the best conditions, in the shortest time, and keep them running through nearly all power supply disturbances of a transient nature. In short, modern synchronous motor control eliminates many of the starting and operating difficulties, which prevented their extensive acceptance in industrial fields.

Modern synchronous motor-control systems comprise the following separate features:

1. Part winding starting, resulting in reduced starting kva.
2. Transfer to full voltage by means responsive to the electrical condition of the field winding.
3. Synchronizing by means responsive to the electrical condition of the field winding.
4. Delayed low-voltage release.
5. Field kick-off and resynchronizing (where the load permits).
6. Unloading and reapplication of load to driven machine.

Not all of these features are required for every application, but those are employed that accomplish best possible starting under all conditions and continuous operation through momentary power or load disturbances.

Electric Furnaces

Several installations of electric furnaces for bright annealing coiled steel strip were completed and placed in operation during the year. Each furnace consists of a bell type heating chamber and several bases or cars upon which the coiled strip is stacked. An inner hood or cover of heat-resisting alloy is placed over the stack and serves to exclude air both during the heating period and while the coils are being cooled. An atmosphere of illuminating gas or other suitable gas is maintained under the hoods to prevent oxidation.

A new type of furnace, applicable especially to annealing steel sheets, has been developed in which a load of material can be cooled in the furnace in a comparatively short time. With previous types, the cooling rate of a loaded furnace is so slow as to make furnace cooling impracticable. The new furnace is lined with light weight refractory brick so that the heat storage in the furnace walls is comparatively small. It employs a circulating system for the furnace atmosphere, with an external cooler by means of which the heat may be extracted and the furnace again charged at a more expeditious rate than was possible heretofore.

Material Handling

There has been installed in the Pittsburgh District a large ore bridge using a bucket of 17 tons capacity. The bridge span is approximately 190 ft. The outstanding feature of the bridge is the unusual use of compressed air for control. Ten motors, 275 to $7^1/_2$ hp., are controlled by electropneumatic type control, similar in design to standard railway equipment. This arrangement, it was found, required less space and lower maintenance. The brakes are spring set and air released for quick, positive stopping. Due to the large volume of air required, there are three sets of compressors and reservoirs, one in the operating cab and one in each leg of the bridge. The bridge in normal service can handle 1,000 tons an hour and serves several blast furnaces located nearby.

Electronic Devices in the Steel Industry

The past year has seen a rapid increase in the number, diversity, and ingenuity of applications of electronic devices in the iron and steel industry. These devices are now controlling shears, soaking pit covers, repeaters, and various mill table operations.

In one plant, a flying shear is located between the intermediate and finishing stands of a 10-inch hot strip mill. This shear is to cut off the relatively cool front end of the bar before it enters the finishing stands. Formerly an operator was necessary to trip the shear when the strip was in the proper position, so as to cut off a definite crop length. Now a photoelectric tube automatically trips the shear. An adjustable time-delay relay is used to determine the time interval between the interruption of the beam of

light and the starting of the shear, thus compensating for the changes in the strip speed.

In another plant, considerable trouble was encountered in maintaining a flag switch on a back blooming mill table, used to control the operation of a recording pyrometer. A photoelectric tube with the required amplifier unit and relays now performs the operation in a more reliable and accurate manner.

Several installations have been made which permit crane operators to control heating furnace doors by means of photoelectric equipment. A number of other steel mill applications of photoelectric devices have been made, such as skip-hoist limit stops, stock-bin level indicators, spotting of material in reheating furnaces, pyrometers, etc.

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All in all, 1931 has, in spite of adverse conditions, brought into being a number of new ideas and electrical developments in the iron and steel industry. Cooperative exchange of information has continued, and permitted the industry to benefit from individual as well as collective effort and development.

The Chairman wishes to express his appreciation for the assistance rendered by the members of the committee in the preparation of this report.

Bibliography

The committee submits a list of the principal papers that have been presented or published by various engineering societies covering more completely many of the subjects reviewed in this report.

1. "Twin Motor Drive," R. H. Wright and H. E. Stokes, *Iron and Steel Engineer*, June 1931, Page 246.
2. "Motor and Control Equipment," F. Mohler, *Iron and Steel Engineer*, June 1931, Page 272.
3. "The Hibbard Control System and Its Application to Synchronous Motors in Steel Mills," W. H. Feldman and S. P. Bordeau, *Iron and Steel Engineer*, December 1931, Page 483.
4. "Electrical Developments in 1931," *Iron and Steel Engineer*, January 1932, Page 7.
5. "Main Drive Statistics—1931," *Iron and Steel Engineer*, January 1932, Page 8.
6. "Electrical Developments in 1931," *General Electric Review*, January 1932, Page 30.
7. "Electrical Developments in 1931," *Electric Journal*, January 1932, Page 25.
8. "A Review of Electrical Developments in the Iron and Steel Industry," W. B. Shirk, *Iron and Steel Engineer*, February 1932, Page 107.
9. "The Application of Electron Tubes in the Steel Industry," D. W. Dean, *Iron and Steel Engineer*, March 1932, Page 124.
10. "Vacuum Tubes and Their Industrial Application," W. C. White, *Iron and Steel Engineer*, March 1932, Page 131.
11. "Electron Tubes in the Steel Industry," L. F. Worden, *Iron and Steel Engineer*, March 1932, Page 136.

Communication

ANNUAL REPORT OF COMMITTEE ON COMMUNICATION*

Committee Affairs

THE Committee on Communication continued the practise of outlining at the beginning of the Institute year tentative communication programs for each of the subsequent scheduled Institute meetings. In making up the year's outline, the Committee strove to select material which would be of broad interest to the Institute as a whole and, in particular, to foster the presentation of papers on subjects that had not been covered before or that had received but little recent attention. A successful endeavor was made to cover such subjects in a rather complete and thorough way. The advance planning of programs greatly aided this by allowing the Committee ample time to solicit authoritative papers discussing all the major aspects of each subject selected for extended treatment.

The more important groups of coordinated papers which in accordance with this general policy have been presented at Institute meetings during the past year are:

Symposium on Communication Services for Power Companies—1931 Summer Convention:

This was prepared with the cooperation of the Committee on Transmission and Distribution and is headed by a general review of the subject prepared by a joint subcommittee of the Committee on Communication and the Committee on Transmission and Distribution, followed by a group of individual papers prepared by power and communication engineers, discussing the solution of this problem in specific cases.

Symposium on Time and Time Services—1932 Winter Convention:

This is headed by two papers discussing the astronomical aspects of time and its measurement, followed by discussions of the time services given by the Naval Observatory, the telegraph companies, and the power companies. In arranging this symposium the Committee on Communication had the cooperation of the Committee on Transmission and Distribution.

Symposium on Traffic Control—Northeastern District Meeting, May 1932:

This is headed by a general discussion of traffic control followed by papers describing various electrical systems now having important fields of application.

Planning for Telephone Toll Service—Southwestern District Meeting, October 1931:

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* COMMITTEE ON COMMUNICATION:

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C. F. Craig,	C. J. Larsen,	C. H. Taylor,
B. R. Cummings,	John Mills,	H. M. Turner,
R. D. Evans,	J. W. Milnor,	F. A. Wolff.
I. C. Forshee,		

A group of three papers discussing, respectively, the forecasting of population, the general advance planning of telephone toll facilities, and certain technical problems involved in their design.

In addition, a number of individual papers has been presented under the auspices of the Committee at various national and regional meetings during the year, discussing important phases of new developments in the telephone, telegraph, and radio arts. The total number of communication papers, including the symposiums, presented at these meetings during the year was 33.

The communication sessions have been very well attended. The Communication Committee proposes to continue during the coming year its plan of developing programs involving groups of coordinated papers covering subjects of broad general interest.

Advance of the Art

In line with the aim to keep this report as short as practicable there are listed below only a few of the outstanding advances made in the field of communication last year.

During the year the Bell System introduced teletypewriter exchange service whereby any subscriber to this new service may secure a direct connection to any other subscriber over which the two may carry on instantaneously reproduced two-way typewritten communication with one another. The methods and switching equipment employed in establishing connections are similar to those employed in telephone practise.

Also during the year the Western Union Telegraph Company and the Postal Telegraph-Cable Company jointly inaugurated a new form of telegraph service known as "Timed Wire Service." This is available to customers who have simplex printers, and provides for the transmission of communications from any printer to any other at rates based on the time the facilities are in use, rather than on the number of words transmitted. Printer customers desiring this service will obtain connection at the central office with an automatic reperforator, which will directly prepare a perforated tape in form for retransmission to the city of destination without additional manual handling. At this point a second perforated tape will be automatically prepared and used for retransmitting the message to the customer addressed. The service is somewhat analogous to a one-way private wire connection, although a direct connection is not established. The Timed Wire Service routine permits of a more economical utilization of the trunk wire plant than would be possible were a direct connection of printers established.

An automatic concentrator was developed for use on printing telegraph circuits to provide faster and more economical service on customers' lines. The Postal Telegraph Company has installed several of these equipments.

A four-wire voice-frequency carrier telegraph system adapted to meet the requirements of a strictly telegraph plant was developed and an initial installation was made on the lines of the Postal Telegraph Company.

A new cable and radio operating center, serving jointly the Commercial Cable Company, the Mackay Cable and Telegraph Company, and All America Cables, was placed in operation last year. Circuits linking the United States with Europe, Central and South America, and the Far East terminate in this center and connect 85,000 miles of under-sea telegraph wires through 19 separate channels. Three cables to Central and South America and two New York-London cables have been equipped with recently developed printer apparatus which has greatly increased the accuracy of reception and has also effected substantial economies. A recently developed method for converting the non-uniform length signals of the Cable Morse Code into a modified 5-unit code, so as to permit of the operation of printers on long non-loaded submarine cables, is employed in connection with these printers.

A pneumatic tube carrier routing device has been developed by the Western Union Telegraph Company for automatically selecting and diverting tube carriers from a main tube into the proper branch tubes. Pneumatic tubes are used to carry telegrams between main and branch offices and between points in large main offices.

Recent achievements in cable making have included the standardization of cables of less than 1,800 pairs employing 26-gage wires, and the application of a new process of insulating small-gage conductors for exchange cables. Under the new method of insulating the cable wires, a coating of wood pulp is applied to each conductor from a bath of water-suspended pulp. This coating when it dries becomes a continuous uniform sleeve of porous paper surrounding the wire. Cables made from this material are of the same size and have practically the same operating characteristics as cables of the older type, for which wires are insulated by helical wrappings of thin, narrow manila paper ribbon. Four machines for producing pulp-insulated wire were placed in operation last year with an output capacity of about 200,000,000 feet of wire a week.

Bermuda, Hawaii, Rio de Janeiro, Java, Sumatra, and the Canary Islands were brought into telephone communication with the interconnected telephone system of North America by means of radio links established in the past year. The first three places are reached by direct radio circuits from the United States. Communication between the sending and receiving stations at Oahu, and the other islands of the Hawaiian archipelago, is secured by an ultra-high-frequency radiotelephone system put into service by the Mutual Telephone Company. This system is also used regularly in inter-island telephone service.

Single side-band transmission of short-wave radiotelephony was successfully demonstrated by the International Telephone and Telegraph Laboratories. The spread side-band system for use on short-wave radio telephone links has also been developed by means of which distortion effects due to selective fading can be largely eliminated. By an extension of the principles involved, a number of side bands can be placed on one carrier in such relative positions

to each other and the carrier that harmonic distortion as well as crosstalk between channels is eliminated.

A successful demonstration of two-way radiotelephony on an 18-cm. wavelength was given across the English Channel by the International Telephone and Telegraph Laboratories. This system, called "micro-ray," employs an antenna only 2 cm. in length. The greater directivity of these short waves makes it possible to employ the same wavelength for a number of separate channels closely spaced as to geographical separation, without mutual interference. Because of this, and the wide frequency band thus opened up, the commercial application of the "micro-ray" would make available nearly a quarter of a million additional radio channels.

Improvements have been made during the year in controllers for pre-timed traffic signals. One type is arranged so that signals may be automatically operated on different time cycles at different periods of the day or week. Another type is primarily intended to operate in connection with a flexible progressive system, but may be also used to meet the special requirements of detached street intersections. This provides for several functions in addition to the usual automatic stop-and-go control: manual control, flashing amber on one street and flashing red on the cross streets, lengthened green on the main street, pedestrian period, fire lane at one or more of the intersections and varying go periods at different intersections, while preserving the total cycle for progression.

1932 Index—A.I.E.E. TRANSACTIONS

Papers and reports contained in the 4 quarterly issues of the 1932 TRANSACTIONS are covered in this annual reference index which is published herewith in an enlarged and improved form. This index embraces all material presented at the Pacific Coast (Lake Tahoe) convention, August 25–28, 1931; the South West District (Kansas City) meeting, October 22–24, 1931; the winter convention, New York, January 25–29, 1932; the Great Lakes District (Milwaukee) meeting, March 14–16, 1932; the North Eastern District (Providence) meeting, May 4–7, 1932; and the summer convention, Cleveland, June 20–24, 1932. Papers informally presented at these meetings (and not published in the TRANSACTIONS) are included, with references to issues of ELECTRICAL ENGINEERING containing these papers in whole or part.

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